Study of foam in Fractures and Porous media for EOR process

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Experimental work:
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Objective:

Study of foaming properties for a surfactant blend with potential to produce ultralow IFT
Introduction:
After preliminary tests of aqueous stability, phase behavior and IFT measurements, the performance of a potential formulation was qualitatively tested. Sand was treated to be oil wet, then immersed and aged with synthetic live oil and finally contacted either seawater or Surfactant solution in seawater.

Silica sand grains were treated to be oil-wet
Using Dichloro octamethyl tetrasiloxane

Hydrophilic

Silica sand

lipophilic
Silica sand was treated with 1,7-Dichloro-octamethyl tetra siloxane, then contacted with synthetic live oil.
After verifying the potential to recover oil, a filterability test was conducted.

Filteration Ratio = \( \frac{t_{200\text{ ml}} - t_{180\text{ ml}}}{t_{80\text{ ml}} - t_{60\text{ ml}}} \)

<table>
<thead>
<tr>
<th>Solution</th>
<th>Filtration Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIW</td>
<td>1</td>
</tr>
<tr>
<td>0.5% A+0.5%B +0.12%E</td>
<td>1</td>
</tr>
<tr>
<td>0.5% A+0.5%B</td>
<td>1.22</td>
</tr>
</tbody>
</table>

Criterion FR> 1.5 unacceptable
Castor 1981
UT Austin FR>1.2 for polymer using 0.45 μm
James Sheng 2010, Modern Chemical EOR
Experiments were conducted to study:

- Foam in porous media (unconsolidated sand pack)
  - Shear thinning properties
  - Effect of permeability
  - Temperature dependence
  - Effect of quality
  - Effect of oil
  - Effect of surfactant concentration
  - Fit parameters of a foam model (MRF Approach)
- Foam in parallel plates as a representation of fractures
Foam: Co-injection of 0.5% A + 0.5%B + 0.12% E
In Seawater at 94° C

80% Foam Quality, OTTAWA Sand K = 45D

Pressure drop (psi)

Overall pressure drop

First tap

Second tap

Gas flowrate (sccm)

Gas flowrate (sccm)

PV (Gas)

Sieve Mesh 200

Silica sand Mesh 35-50

Rubber stopper

Rubber stopper 5 1/2

Rubber stopper

Rubber stopper 5 1/2

Rubber stopper

Silica sand Mesh 35-50

First Tap

Second Tap

Sand pack Internal-Tap Locations

80% Foam Quality, OTTAWA Sand K = 45D

Gas flowrate (sccm)

PV (Gas)

Overall pressure drop

First tap

Second tap

Pressure drop (psi)
Foam: Co-injection of 0.5% A + 0.5% B + 0.12% E
In Seawater at 94°C

Shear thinning effect

Experimental data
80% quality

Model fit
n = -0.81
Effect of permeability

\[ F_4 = \left( \frac{u_g}{\sqrt{k \phi}} \right)^{epv} \frac{1}{1.53 \, s^{-1}} \]

1% Surfactant (25C)
\[ \Gamma = 0.65 \]
0.05-1.2 darcy
(Parlar, 1995)
Effect of foam Quality

Experimental data

Foam : Co-injection of 0.5% A + 0.5% B + 0.12% E
In Seawater at 94° C

Total flow rate 1.9 cm³/min
u = 22.2 ft/day

Apparent viscosity (cP)

Foam Quality
# Parameters for the model

## Porous media and fluids properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D$</td>
<td>2.29 cm</td>
</tr>
<tr>
<td>$L$</td>
<td>36.195 cm</td>
</tr>
<tr>
<td>$k$</td>
<td>44 darcy</td>
</tr>
<tr>
<td>$\phi$</td>
<td>0.36</td>
</tr>
<tr>
<td>$\Delta L$</td>
<td>15.24 cm</td>
</tr>
<tr>
<td>$S_{cw}$</td>
<td>0.1</td>
</tr>
<tr>
<td>$S_{rg}$</td>
<td>0.05</td>
</tr>
<tr>
<td>$n_w$</td>
<td>5</td>
</tr>
<tr>
<td>$n_g$</td>
<td>2</td>
</tr>
<tr>
<td>$k_w^0$</td>
<td>1</td>
</tr>
<tr>
<td>$k_g^0$</td>
<td>1</td>
</tr>
<tr>
<td>$\mu_w$</td>
<td>0.3 cP</td>
</tr>
<tr>
<td>$\mu_g$</td>
<td>0.02 cP</td>
</tr>
</tbody>
</table>

Equation:  
\[
k_{rw} = k_{rw}^0 \left( \frac{S_w - S_{cw}}{1 - S_{rg} - S_{cw}} \right)^{n_w}
\]

## Parameters for the model after fitting

- $ep_{dry}$: 100
- $fmd_{dry}$: 0.15
- $fmmob$: 140500
- $ep_{v}$: -0.81
- $U_{ref} (m/s)$: $1.00E-05$

Equation:  
\[
F_2 = \frac{1}{2} + \frac{1}{\pi} \arctan \left[ ep_{dry}(S_w - fmd_{dry}) \right]
\]

Equation:  
\[
F_4 = \left( \frac{u_g}{u_{gref}} \right)^{ep_{v}}
\]
Parameters for the model: observation comparison and suggestion

Comparison of Foam strength at same shear rate with previous recommended formulation: B+A₂ 2:1

Shown as continuous black line

Foam quality 80%

$F_4 = \left( \frac{u_g / \sqrt{k\phi}}{1.53 \text{ s}^{-1}} \right)^{epv}$

Fits to all values of permeability studied 100, 44, 8 and 2 darcy

Apparent shear rate (Carreau, 1997)

$\dot{\gamma} = 12u_g / \sqrt{75k\phi} \approx 1.385u_g / \sqrt{k\phi}$

$F_4 = \left( \frac{1.385u_g / \sqrt{k\phi}}{3.505 \text{ s}^{-1}} \right)^{epv}$
Effect of Oil on Foam Strength at 70% quality

Two transient tests
Flow increased at 0.1 PV of gas from 0.12 cm³/min to 1.87 cm³/min
- foam recovered its strength in less than 1PV of gas
- oil injection at 2.27 PV of gas, took close to 0.1 PV of gas injection to see the oil BT

Injection of 5% PV of oil during co-injection
The surfactant concentration in the range from 0.14% m/v to 1.12 % has no effect on the foam strength at steady state for quality between 75% and 80%.
Effect of surfactant concentration

The dependence of foam strength with surfactant concentration is stronger when the quality is less than 80%.

Total flow rate 1.9 cm³/min

\[ V = 22.2 \text{ ft/day} \]
Foam in fractures
Diagram of Experimental Set Up

Mass Flow Controller

Pump

N₂

Surfactant solution

Transducer

Parallel Plates

Closed

Ports

Safe Relief

Frit

3psi

FOAM

Diagram of Experimental Set Up
Picture of Experimental Set Up for Foam Testing

Model encased for mitigating glass glare in videos/pictures.
Experimental variables

- Flow, $cm^3/min$: 19.2, 9.6, 4.8 (604 ft/day)
- B/A Ratio: 100/0, 75/25, 50/50 + 0.12% E
- % Quality: 52, 71, 88

Ultra low IFT between Oil and aqueous phase

$L = 25 \, cm$, $H = 15 \, cm$, $b=0.025 \, cm$
Effect of frit size to pre-generate foam
Foam in 250 μm aperture parallel plates 25° C

7.5B: 2.5 A
60 μm _ Solid line_ closed circles
90 μm _ Dashed line_ open circles

Pressure drop (psi)

Foam Quality
- 88%
- 71%
- 52%
Apparent viscosity

7.5 B : 2.5 A

\[ \mu = k \frac{V_p}{q} \]

\[ k = \frac{b^2}{12} \]

\[ b = \text{fracture thickness} = 250 \, \mu m \]

\[ k = 5260 \text{ Darcy} \]

~100 ft/day

Foam Quality

- 88%
- 70%
- 52%
Comparison of Surfactants (1)

Pre-generated foam (60 μm frit)

7.5 B : 2.5 A

BLEND: Open circles
- Red: 88%

A : Closed circles
- Red: 88%
- Purple: 71%
- Blue: 52%

B : open diamonds
- Red: 88%
- Purple: 71%
- Blue: 52%
1% 5 B/ 5 A + 0.12 % E

Flow cm³/min

12.9

9.6

4.8

0.8

Quality 50 % 70% 90%
Remarks:

• \( \text{N}_2 \) Foam of blended \( \text{B:A} \) is stronger than B or A

\begin{align*}
\text{B} & \text{ creates weaker foam, more segregation than A.} \\
\text{A} & \text{ creates stronger foam than B but weaker than blend}
\end{align*}

• 1% 5/5 B/A + 0.12% E - \textit{of ultra low tension}- creates strong foam, and no segregation under studied conditions.

• The sizes of frit studied produced practically insignificant differences among test results
According to Falls et al. (1989) four components of viscosity can be listed:

1. Newtonian viscosity of any liquid slugs between gas bubbles
2. Resistance of interface deformation, viscous resistance of liquid between the foam bubbles and capillary wall
3. Surface traction from surface tension gradient in surfactant concentration
4. Pore constrictions resistance

Zhang et al. (2009) Suggested the most important terms are (2) and (4)

Test results from Foam Generation in parallel plates and sand packs are consistent with work done by Falls et al.:

The contribution of pore constrictions to the viscosity of foam was observed when Porous media and Parallel plate test results were compared
Porous media vs parallel plate: Sand pack and glass plates

Apparent shear rate in sand pack
\[ \dot{\gamma}_{SP} = 12 \frac{u}{\sqrt{75 k \phi}} \]

Silica sand:
44 darcy
Foam quality 80%
By Andres

Apparent shear rate in parallel plates
\[ \dot{\gamma}_{PM} = 6 \frac{u}{(\Delta x)} \]

Parallel plates:
Aperture 250 μm
Frit: 90 μm
Foam quality 88%
By Angelica

Viscosity (cP) vs Shear rate (1/s)

Shear thinning including pore constriction
\[-1 < n = -0.81 < -1/3\]

Shear thinning without pore constriction
\[-2/3 < n = -0.45 < -1/3\]

Falls et al. (1989)
Conclusions

• Surfactant with potential to recover oil produced strong foams in sand packs at reservoir temperature.
• The formulation is robust in concentrations from 0.14 to 1.12\% in seawater.
• Foam strength is recovered after recovering all the crude oil.
• Parameters of a foam model were fitted using experimental data in a wide range of fractional flows, permeabilities and flow rates.
• The foam is strong not only in porous media, but fractures represented by parallel plates.

Future studies

• Foam in parallel plates should be evaluated in presence of oil, different temperatures and concentrations.
• The modeling of foam in porous media and fracture should be combined to simulate the performance of foam in the field.
Acknowledgements : PEMEX
End of Presentation
Sandpack Internal-Tap Locations

First Tap
- Rubber stopper
- Silica sand Mesh 35-50
- Sieve Mesh 200
- Internal Taps
- 1.5"
- 6"

Second Tap
- Rubber stopper
- Rubber stopper 5 1/2
- Rubber stopper
- Rubber stopper 5 1/2
- Sieve Mesh 200
- Internal Taps
- 1.5"
- 6"
\[ k_{rg}^f = k_{rg}^0 \left[ 1 - \frac{S_w - S_{wc}}{1 - S_{gr} - S_{wc}} \right]^{ng} \]
Parameters for the model
(observance comparison and suggestion)

Foam strength comparison with previous formulation (B+A₁ 2:1)
Shown as continuous black line
Foam quality 80%

\[ F_4 = \left( \frac{u_g}{\sqrt{k\phi}} \right)^{epv} \]
This function fits to all the values of permeability studied:
100 darcy, 44 darcy, 8 darcy and 2 darcy

Apparent shear rate (Carreau, 1997)
\[ \dot{\gamma} = 12 \frac{u_g}{\sqrt{75 k\phi}} \approx 1.385 \frac{u_g}{\sqrt{k\phi}} \]

See Appendix A
Foam quality 80%

Apparent viscosity (cP)

Total flow rate (cm$^3$/min)

0.5% B + 0.5% A + 0.12% E

1 ft/day

Previous recommended formulation
Shear thinning including pore constriction  \[-1 < n = -0.81 < -\frac{1}{3}\]

Shear thinning without pore constriction  \[-\frac{2}{3} < n = -0.45 < -\frac{1}{3}\]

Falls et al. (1989)
<table>
<thead>
<tr>
<th>Sample</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
<th>VII</th>
<th>VIII</th>
<th>IX</th>
<th>X</th>
<th>XI</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS in SW</td>
<td>100</td>
<td>90</td>
<td>80</td>
<td>70</td>
<td>60</td>
<td>50</td>
<td>40</td>
<td>30</td>
<td>20</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>FB</td>
<td>0</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>40</td>
<td>50</td>
<td>60</td>
<td>70</td>
<td>80</td>
<td>90</td>
<td>10</td>
</tr>
</tbody>
</table>

Surfactant solution in seawater
Formation Brine
Abstract:
A formulation to obtain ultralow IFT for EOR application is evaluated to be transported as a foam in a fractured porous media. The evaluation process includes tests from room up to reservoir temperature 120°C in sandpacks, rubblized porous media and parallel plates. Surfactant solutions used were prepared in seawater. Experimental results were used to fit parameters of a mathematical model to describe the foam using the mobility reduction factor approach. The experimental study includes, shear thinning effect, dependence on quality, temperature, permeability, presence of oil and surfactant concentration.
Sand was treated to be oil wet, then equilibrated with synthetic live oil for couple of days and then contacted either formation brine or Surfactant solution in sea water.

Silica sand grains were treated to be oil-wet
Using Dichloro octamethyl tetrasiloxane
Glass micro channels were treated to be oil-wet
Dichlorodimethylsilane
• Screening of Surfactants for foam applications
  • Surfactant blend should be tolerant to divalent ions.
  • Should be stable in the range of Temperature of interest (25°C-120°C)
  • In tests of front dilution should not precipitate.
  • Filterability test must demonstrate unplugging.
**IFT of formulations with added N and L {surface active}**

<table>
<thead>
<tr>
<th>Formulation</th>
<th>N and L Concentration</th>
<th>IFT in Dynes/cm in Seawater at 100°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5B/2.5A</td>
<td>0.15% S61</td>
<td>4.3E-1</td>
</tr>
<tr>
<td>7.5B/2.5A</td>
<td>0.04% N58</td>
<td>3E-1</td>
</tr>
<tr>
<td>5B/5A</td>
<td>0.04% N58</td>
<td>2E-3</td>
</tr>
<tr>
<td>5B/5A</td>
<td>0.11% N58</td>
<td>2E-2</td>
</tr>
<tr>
<td>5B/5A_{6.4}</td>
<td>0.3% N58</td>
<td>3E-2</td>
</tr>
<tr>
<td>5B/5A_{6.4}</td>
<td>0.3% C16 **</td>
<td>2.2E-2</td>
</tr>
<tr>
<td>5B/5A</td>
<td>0.12% L38</td>
<td><strong>1E-3</strong></td>
</tr>
</tbody>
</table>

*IFT in Dynes/cm in Seawater at 100°C*
Transient experiments (qualitative)

9.4 cm³/min upward flow

Apparent Viscosity (cP)
Effect of Oil on Foam Strength at 70% quality, 94°C Part 2 of 3

Total flow rate 1.87 cm³/min (ca 19.4 ft/day)

Injection of 5% PV of oil during co-injection

Tap 1

Tap 2
Effect of Oil on Foam Strength at 75% quality, 94°C _Part 1 of 3_
Total flow rate 0.78 cm³/min (ca 8 ft/day)
Foam experimental set up for high temperature
Comparison of foam strength for different surfactants at 94°C and 1% total surfactant concentration in a sand pack, using qualities between 60 - 70%. Straight lines are for power law fit ($n \approx 0.8$).
Minimum velocity to foam

\[ F_5 F_6 \approx k_1 \left( \frac{u}{u_{ref}} \right)^{epcap - epn} \left( 1 - \frac{u_{ref}}{u} \right)^{epn} \]

Assumption:

\[ ep cap = ep n. \]

using a value for \( ep cap = 3 \)

Results are consistent with observation done by Cheng et al (2000), where he establish a relationship with the shear thinning exponent and the parameter ep cap

\[ \sigma = \frac{1}{1 + ep cap} \]

Simulation of the foam viscosity using the mobility reduction factor approach. The symbols are experimental data at gas quality close to used in the simulation of 70%.
Frames from inlet section during horizontal flow

~30 Sec

time interval

10 Sec

Foam

Surfactant solution

Oil
2-D Model*
Mimicking a Fracture for Study of Foam

*Adapted by Maura Puerto 2013 from Wei’s Thesis 2006
Transient experiments (upward vs downward)

9.4 cm³/min
Downward flow

9.4 cm³/min
Effect of Quality

Foam in 250 μm aperture parallel plates 25° C

60 μm Frit

7.5 B : 2.5 A

Foam Quality
- 88%
- 71%
- 52%
José Luis López-Salinas (Thesis, 2013)  
*Transport of Components and Phases in a Surfactant/Foam EOR Process for a Giant Carbonate Reservoir.*

**Estimation of Parameters for the Simulation of Foam Flow through Porous Media. Part 1: The Dry-Out Effect**  
Kun Ma, Jose L. Lopez-Salinas, Maura C. Puerto, Clarence A. Miller, Sibani Lisa Biswal, and George J. Hirasaki*  
*Energy Fuels*, 2013, 27 (5), pp 2363–2375  
DOI: 10.1021/ef302036s  
Publication Date (Web): May 3, 2013  
Copyright © 2013 American Chemical Society

**Non-uniqueness, Numerical Artifacts, and Parameter Sensitivity in Simulating Steady-State and Transient Foam Flow Through Porous Media**  
Kun Ma · Rouhi Farajzadeh · Jose L. Lopez-Salinas · Clarence A. Miller · Sibani Lisa Biswal · George J. Hirasaki  
DOI 10.1007/s11242-014-0276-9

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For More Information See: