The National IOR Centre of Norway
Preliminary Postdoc report (Bergit Brattekås), part of

Integrated EOR for heterogeneous reservoirs

Project 1.1.9

Project manager: Bergit Brattekås
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Project duration: June 2014 – August 2018

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Preliminary Project Report

Integrated EOR for heterogeneous reservoirs

Project number and location (UiS, IRIS, IFE): PR-10371-01, UiS (in collaboration with UiB)
Project duration:
Phase 1: June 2014 – December 2015
Phase 2: January 2016 – August 2018*
*Phase 2 is a 2 year Post Doc project. The project was inactive for eight months in 2016, due to Post Doc/project leader on maternity leave (no reporting/use of budget in this period).
Project manager: Bergit Brattekås
PhD students and postdocs: Bergit Brattekås (Post Doc)
Other key personnel: Bergit Brattekås is supervised by Arne Stavland (IRIS), Martin A. Fernø (UiB) and Geir Ersland (UiB). Arild Lohne (IRIS), Aksel Hiorth (IRIS/UiS), Pål Østebø Andersen (Post Doc at UiS) and Oddbjørn Nødland (PhD student at UiS/IRIS) are involved in the project. 6 master students have so far been supervised by the project leader during the project. Two more will complete their MSc degree in june.

1. Executive summary

This document is a final report of Phase 1 of the project "*Integrated EOR for heterogeneous reservoirs*", and a preliminary report for Phase 2, providing the status quo after 1 year and 4 months of active project time (the 2 year project will be finalized in august). The project aims to develop integrated EOR (iEOR), using mobility control and chemicals/fluids in a smart sequence, which relates to Milestone 1 of the IOR Centre road map. Another important part of this project is to use experimentally measured data as an input in IORcoreSIM, to gain knowledge and understanding of IOR mechanisms, which relates to Milestone 3 of the IOR Centre road map. The focus of the project continuously shifts between experimental work on the core scale, and modelling and simulation of the results. Scientific details from this research may be found in the quarterly reports, as well as in the published papers listed under bullet point 3 (Results) in this report.

The scientific progress of the project is often exemplified by polymer gel in this report. It may, however, be argued that an aspect of similar importance is the continuous interaction between experiments, modelling and simulations necessary to progress in all three fields simultaneously. A good work flow between modellers and experimentalists has been established, and two collaborative papers has this far been published/accepted. The experimental work has been performed at the University of Bergen, by the Post Doc/project leader and associated master students. Modelling has been performed at IRIS/UiS, with input from the experimental group at UiB. Modelling and simulation efforts have indicated weaknesses in some experimental setups, which have then been modified. Prevailing mechanisms of flow suggested by the simulation work were often verified, or in some cases deemed unlikely, by the individuals performing experiments. The multi-disciplinary research in this project has focused on the mechanisms involved in spontaneous imbibition, in both brine/oil and polymer gel/oil systems.

2. Introduction and background

Maintaining hydrocarbon production from mature fields is an important challenge in the world today, also on the Norwegian Continental Shelf (NCS), and several EOR methods have been designed and developed in the last several decades for this purpose. Many have, however, delivered less than expected results, often attributed to the presence of fractures or high-permeability streaks in the reservoir. Channelling of injected EOR fluids through highly conductive pathways may cause an early fluid breakthrough and low production oil cut, because the injected EOR chemicals contact less of the reservoir than expected. Mobility control by polymer gel and foams may enhance oil recovery by reducing heterogeneous flow in the reservoir. Efficient reduction of fracture conductivity by either method causes diversion of fluids into the matrix to displace oil. Reduction of sea water pollution due to waste water is a common side effect of successful mobility control: handling of produced water, often containing traces of the EOR chemicals, is a big challenge for the E&P industry.

Improved understanding of mobility control by polymer gel and foam has been achieved through this project. We have focused on three main tasks: 1. Optimize polymer gel and foam mobility control, 2. Use improved mobility control in Integrated Enhanced Oil Recovery (iEOR), 3. Numerical modelling and upscaling of iEOR. The experimental work in this project was performed at the University of Bergen, by the Post Doc/project leader and associated master students. Modelling and simulation of experiments has been performed at IRIS/UiS.

3. Results

The main results for each task are summarized below.

1. Optimize polymer gel and foam mobility control

Foam and polymer gel, and combined methods (e.g. Polymer-Enhanced Foams (PEFs), Foamed Gels (FGs)) have been investigated to determine optimum in-depth conformance control. Although methods like e.g. polymer gel has been investigated for decades, detailed knowledge about its behavior is necessary to accurately predict its performance in the field. This project contributes to increased understanding of conformance control by ***I)*** performing core scale experiments, and ***II)*** modelling the experiments, aiming to simulate the experimental results and upscale the mechanisms to larger scales. Two important results following from these subtasks will be presented at SPE IOR in Tulsa in April: Although polymer gel behavior is frequently evaluated in single phase flow tests in the laboratory, laboratory work performed in this project shows that multiphase functions, such as capillary pressure and relative permeability, influence conformance control, contradictory to best-practice today. Brattekås *et al* (2018) presents experimental work and analyze the influence of the results on gel dehydration during placement. Previous work [1] showed that water bound in a polymer gel network may imbibe into an adjacent oil-saturated matrix, which causes changes in the gel network. Modelling of this effect is important in order to understand and quantify gel behavior in oil-bearing zones in a fractured reservoir, and is presented in Andersen *et al* (2018).

2. *Use improved mobility control in Integrated Enhanced Oil Recovery (iEOR)*

Combining EOR methods with mobility control in specially designed, integrated processes (iEOR) was previously shown to increase oil recovery from oil-wet, heterogeneous systems by significantly improving sweep efficiency. Oil recovery was observed to depend on the chase fluid, which largely controls the shape of the displacement front and thus the macroscopic sweep efficiency [2]. Smart sequences of fluid injection after conformance control treatments may be designed to significantly enhance oil recovery. Important implications from this research were observed when polymer gel treatments were combined with subsequent low-salinity waterfloods: Gel performance was significantly improved during low-salinity water injection. High pressure gradients during chasefloods may cause gel to rupture, which opens up parts of the gel treated fracture volume to flow and reduces the gel ability to block fractures. During low-salinity waterflooding through ruptured gel, this effect was reduced and matrix flow was restored. In some cores, the fracture was re-blocked by gel during low-salinity waterflooding and fluid flow occurred through the matrix only. The effect was reversible: increasing the salinity of the water phase influenced the gel in the fracture, and re-opened parts of the fracture volume to flow. These results indicate the flexibility of conformance improvement treatments using complex fluids, like foam and gel.

The midterm evaluation report by the Norwegian research council: "Midterm evaluation of research centres for petroleum activities" (December 2017) stated that: *"… it is important to distinguish here, and in all the activities, the difference between: (a) polymers used proactively in association with water injection (i.e., polymer flood, low salinity + polymer, surfactant flood + polymer) where the use of the polymer is designed into the flood to optimise sweep; and (b) polymers and silicates designed to be used reactively to remediate problems that arise with sweep, using treatments near the well (e.g., cross-linked polymer gels) or deeper into the reservoir (e.g., thermally activated polymers and silicates). Both these modes are important but (a) has much higher recovery impact on the Norwegian Continental Shelf. Operationally these are very different and the way in which they would be incorporated into reservoir optimization would need to be different."*

This project has shown (Task 2 especially) that polymer gels are a useful, and sometimes necessary, first step in integrated EOR. Optimized sweep can be achieved with smart design of the chase flood process, potentially with a high impact on recovery (also on the NCS).

3. *Numerical modelling and upscaling of IEOR*.

Formed gels behave differently from polymer solutions, and incorporating their behaviour into simulation software must be handled separately. Task 3 of this project has incorporated gel networks and corresponding behaviour into IORcoreSIM with good results (Andersen et al, 2018). The task aims to include IEOR methods and process mechanisms in numerical simulators, in a way that is both representative and accurate; first on core scale, thereafter on reservoir grid and field scale. I.e: this task connects to task 1 and Task 2 above.

The results from the research in this project are summarized in the following lists of papers (publications are listed for each project phase), published master thesis and other achievements:

Peer-reviewed papers

Phase 1:

1. Fernø, M.A., Haugen, Å., **Brattekås, B**., Mason, G. and Morrow, N.: *"Quick and Affordable SCAL: Spontaneous Core Analysis"*, Reviewed proceedings at the International Symposium of the Society of Core Analysts, St.John's, Newfoundland&Labrador, Canada, 16-21 August 2015.

2. **Brattekås, B.**, Pedersen, S.G., Nistov, H.T., Haugen, Å., Graue, A., Liang, J-T. and Seright, R.S.: "*Washout of Cr(III)-Acetate-HPAM Gels From Fractures: Effect of Gel State During Placement*." SPE Production & Operations **30**(02): 99-109, May 2015.

3. Eide, Ø., Ersland, G., **Brattekås, B.**, Haugen, Å., Graue, A. and Fernø, M.A.: *"CO_2 EOR by Diffusive Mixing in Fractured Reservoirs"*, Petrophysics, **56** (01), 23-31, February 2015.

Phase 2 (preliminary):

4. **Brattekås, B**. and Seright, R.S.: *"Implications for improved polymer gel conformance control during low-salinity chase-floods in fractured carbonates"*, Journal of Petroleum Science and Engineering, available online Oct 20, 2017. 10.1016/j.petrol.2017.10.033

5. **Brattekås, B.,** Steinsbø, M., Graue, A., Fernø, M.A., Espedal, H. and Seright, R.S.: *"New Insight Into Wormhole Formation in Polymer Gel During Water Chase Floods With Positron Emission Tomography",* SPE Journal 22(01), February 2017.

6. **Brattekås, B.,** Graue, A. and Seright, R.S.: *"Low Salinity Chase Waterfloods Improve Performance of Cr(III)-Acetate HPAM Gel in Fractured Cores"*, SPE Reservoir Evaluation & Engineering 19(02), April 2016.

7. **Brattekås, B.** and Fernø, M.A.: *"New Insight from Visualization of Mobility Control for* ***Enhanced Oil Recovery using Polymer Gels and Foams"*****, chapter published in** *CHEMICAL ENHANCED OIL RECOVERY (CEOR)- A PRACTICAL OVERVIEW*. INTECH 2016 ISBN 978-953-51-2700-0. s. 101-122, October 2016.

Other publications (conference papers, reports, etc)

Phase 1:

8. **Brattekås, B.,** Graue, A., Seright, R.S.: ***"****Low Salinity Chase Waterfloods Improve Performance of Cr(III)-Acetate HPAM Gel in Fractured Cores****"***, SPE 173749, presented at the SPE International Oilfield Chemistry Symposium held in the Woodlands, Texas, 13-15 April 2015.

9. Steinsbø, M., **Brattekås, B.**, Bø, K., Oppdal, I., Tunli, R., Ersland, G., Graue, A. and Fernø, M.A.: *"Foam as Mobility Control for Integrated CO_2-EOR in Fractured Carbonates"*, presented at the EAGE 18th European Symposium on Improved Oil Recovery held in Dresden, Germany, 14-16 April 2015.

10. Fernø, M.A., Haugen, Å., **Brattekås, B.**, Morrow, N.R. and Mason, G.: *"Spontaneous Imbibition Revisited: A New Method to Determine Kr and Pc by Inclusion of the Capillary Backpressure"*, presented at the EAGE 18th European Symposium on Improved Oil Recovery held in Dresden, Germany, 14-16 April 2015.

11. Fernø, M.A., Gauteplass, J., Hauge, L.P., Ersland, G., Abell, G.E., Adamsen, T.C.H., Steinsbø, M., **Brattekås, B.** and Graue, A.: *"Combined PET-CT for Visualization and Quantification of Fluid Flow in Porous Rock Samples",* presented at the Medviz conference 2015: Innovation in Imaging and Visualization held at Haukeland University Hospital in Bergen, Norway, 15-16 June 2015.

12. **Brattekås, B.**, Haugen, Å., Ersland, G., Graue, A., Fernø, M.A., Seright, R.S.: *"Influence of Rock Saturation and Wettability on Polymer Gel Placement and Stability in Fractured Rocks"*, presented at ComFlowPore15: Complex Fluid Flows in Porous Media held in Bordeaux, France, 12-14 October 2015.

13. **Report by Arild Lohne: "***Spontaneous imbibition from gel"*, 22/4-2016 (Internal report)

Phase 2 (preliminary):

14. **Brattekås, B.,** Steinsbø, M., Graue, A., Fernø, M.A, Espedal, H. and Seright, R.S.: *"New Insight to Wormhole Formation in Polymer Gel during Water Chasefloods using Positron Emission Tomography (PET)***,** presented at SPE Oneday seminar, held in Bergen, Norway, 20 April 2016.

15. Pål Ø. Andersen, **Bergit Brattekås**, Kenny Walrond, Daisy S. Aisyah, Oddbjørn Nødland, Arild Lohne, Håkon Haugland, Tore L. Føyen, and Martin A. Fernø: "*Numerical Interpretation of Laboratory Spontaneous Imbibition - Incorporation of the Capillary Back Pressure and How it Affects SCAL"*, presented at the Abu Dhabi International Petroleum Exhibition and Conference, ADIPEC17, held in Abu Dhabi, UAE, 13-16 November 2017.

16. **Brattekås, B.**, Ersland, G. and Seright, R.S.: *"Solvent Leakoff during Gel Placement in Fractures: Extension to Oil-Saturated Porous Media"*, presented at the SPE Improved Oil Recovery Symposium, Tulsa, Oklahoma, USA, 14 – 18 April 2018.

17. Andersen, P.Ø., Lohne, A. Stavland, A., Hiorth, A. and **Brattekås, B.**: *"Core Scale Simulation of Spontaneous Solvent Imbibition from HPAM Gel"*, presented at the SPE Improved Oil Recovery Symposium, Tulsa, Oklahoma, USA, 14 – 18 April 2018.

18. Føyen, T., **Brattekås, B.** and Fernø, M.A.: *"Onset of Spontaneous Imbibition"*, presented at the SPE Improved Oil Recovery Symposium, Tulsa, Oklahoma, USA, 14 – 18 April 2018.

Master students supervised during the project period:

2016

University of Bergen (co-supervisor):

- Trond Vabø: "Viscosity Effects on Imbibition Rate and Front Behavior during Co-Current Spontaneous Imbibition in Unconsolidated Porous Media"
- Silje Lande: "Polymer Enhanced Foam in Unconsolidated Sand"
- Håkon Haugland: "Spontaneous Imbibition in Sand - Viscosity Effects on Oil Recovery and Flow Using Polymer and Glycerol"

2017

University of Bergen: (main supervisor):

- Tore Lyngås Føyen: "Onset of spontaneous imbibition"
- Andreas Grøteide Polden: "Foam generation and flow in fractures with different apertures"
- Petter Davanger Solberg: "Polymer enhanced foams and flow regimes in unconsolidated sand"

Other achievements:

Best Technical Presentation award at SPE Bergen One Day Seminar, April 20, 2016 (Bergen, Norway) for the paper "New Insight to Wormhole Formation in Polymer Gel During Water Chasefloods Using Positron Emission Tomography (PET)"(SPE-180051-MS). The paper was featured article in Journal of Petroleum Technology (JPT) in November 2016.

4. Conclusion

The project has this far resulted in 18 published papers (7 of them peer-reviewed). 9 of the papers are published in Phase 2 this far. The project will be completed in August, and the final report submitted.

5. Future work/plans

Three conference papers will be presented at SPE IOR 2018 in Tulsa this April (of which at least two will be submitted to an SPE journal). The project will be presented at IOR Norway 2018. Two master students connected to the project will deliver their master thesis in June.

6. Dissemination of results

Please see 4. "Results" above

7. References

1. Brattekås, B., et al., *Gel Dehydration by Spontaneous Imbibition of Brine from Aged Polymer Gel.* SPE Journal, 2014. **19**(01): p. 122-134.

2. Brattekås, B., et al., *Fracture Mobility Control by Polymer Gel- Integrated EOR in Fractured, Oil-Wet Carbonate Rocks*, in *EAGE Annual Conference & Exhibition incorporating SPE Europec*. 2013: London, UK.