The National IOR Centre of Norway.
Final Post Doc report (Pål Østebø Andersen), part of:

Adding more physics, chemistry and geological realism into the reservoir simulator

Project 2.6.1

Project manager: Robert Klöfkorn
Postdoc: Pål Østebø Andersen
Key personnel: N/A
Project duration: September 2014 – October 2018

The National IOR Centre of Norway

Final Post Doc Project Report

Part of project 2.6.1: Adding more physics, chemistry and geological realism into the reservoir simulator.

Project number and location (UiS, IRIS, IFE):	Theme 2, Task 6.1, located at UiS
Project duration:	The original post doc contract; 3 years (Sep 2014 to Sep 2017). Was extended by one year to Sep / Oct 2018
Project manager:	Robert Klöfkorn
PhD students and postdocs:	Pål Ø. Andersen (PostDoc)
Other key personnel:	N/A

1 Executive summary

The following briefly summarizes the work performed by postdoc Pål Ø. Andersen on Task 6.1 in Theme 2 during both the original three year contract period Sep 2014 to Sep 2017, and the extension until Sep 2018.

The project aims at developing tools for translating lab geochemical and physical effects coupled to multiphase flow in porous media or EOR mechanisms towards the field scale. This includes interpreting core scale experimental results where chemistry is important for compaction, single phase and multiphase flow and suggest how that will appear in larger scale models.

An example is fracture-matrix models where ionic components are transported in a mobile domain and must diffuse into a matrix in order to affect the main volume. The developed methodology allows combining reservoir heterogeneity with full discretization of the matrix blocks, i.e. no upscaling of the diffusion and EOR processes to transfer functions. The fracture-matrix approach is also applied in a shale gas context where gas is produced by hydraulically induced fractures near well perforations. This work is related to supervision of a PhD student (Dhruvit Berawala) where we transfer some of the knowledge from working on naturally fractured reservoirs.

We have developed a new methodology for porous media two-phase flow where viscous coupling is included into the fundamental equations from a mixture theory approach. This allows prediction of variations in relative permeability functions due to changes in flow regime and viscosity and is important for translating measurements to other flow conditions that naturally can vary locally and with time.

Much work has also been dedicated to Special Core Analysis, i.e. models for interpreting measurement setups for capillary pressure and relative permeability. In this regard we have explored centrifuge, core flooding, porous disc setups and developed a new capillary pressure correlation. Mainly, this concerns finding time scales for establishing steady state in a system given the applied boundary conditions and determining saturation functions in new ways. Some of the mathematical models were tested experimentally in MSc projects.

As one of the three first contract years was paid by the Department of Petroleum

Technology (IPT) at UiS, significant time was dedicated to teaching (PET565 Core Scale Modelling and Interpretation) and supervision of students on BSc, MSc and PhD level. Teaching an additional course (PET670) was a requirement for extending the contract to 2018.

2 Introduction and background

The main focus of my work has been to develop numerical and analytical models relevant for multiphase and / or reactive flow in porous media. This includes:

- Fracture-matrix models that can simulate naturally fractured reservoirs and hydraulically fractured shale.
- Model experimental studies on reactive flow in chalk in collaboration with the Chalk Group at UiS.
- Developing simplified analytical models for SCAL measurements. This includes centrifuge test time scale and capillary end effects during water flooding.
- Evaluate capillary back pressure effects during spontaneous imbibition. This was used to model experimental data from UiB, in collaboration with them and NORCE.
- Multiphase model with viscous coupling for prediction of how data measured in the lab may perform in different flow settings.
- Characterization of WAG performance using a universal mobility ratio.
- Modeling of nanoparticle interactions during core flooding.

The collaboration network involved roughly 30-40 people mainly from UiS, UiB, IRIS (now NORCE), Statoil (now Equinor) including students and employees. See the reference lists for details.

3 Results

Several mathematical modelling works have been developed with the purpose of:

- Adding new elements or assumptions as alternative approaches to existing models. This includes a mixture theory approach to model multiphase flow instead of conventional Darcy-type flow and allows for accountancy of viscous coupling.
- Interpreting chemically reactive flow in porous media from core scale tests and implement the results to higher scale.
- Simplifications of conventional systems, especially regarding SCAL setups (porous disc, centrifuge, core flooding) or for naturally fractured reservoirs where a fracture-matrix approach has been followed.
- Scaling complex systems to determine controlling mechanisms and limiting behavior when one mechanism is dominating.

The work has demonstrated more intuitive understanding of generally complex systems and ways of translating main effects from core scale to a higher scale.

A broad network of collaborators has been established regarding research activity, especially within UiS, IRIS (now NORCE) and UiB. This involves employees from experimental and modelling background, but also students (BSc, MSc, PhD). Much collaboration and research has been done together with Dag Standnes from Statoil / UiS. Several meetings or plans were

made with the SCAL group in Statoil, Valide and IRIS Bergen (mainly with Robert Klöfkorn).

4 Conclusion(s)

We have developed

- fracture-matrix models to interpret flow in naturally fractured reservoirs and shale gas reservoirs.
- models for upscaling lab scale experiments.
- time scales and simplified models for SCAL setups.
- a multiphase flow model to account for viscous coupling.
- a new capillary pressure correlation.

5 Future work / plans

Not relevant.

6 Work in progress

Not relevant.

7 Dissemination of results

Mainly includes journal and conference papers, (master) theses, presentations and posters.

8 References (including postdoc work published after the contract)

Journal papers

1. Andersen, PØ, Brattekås, B, Nødland, OM, Lohne, A, Føyen, TL, Fernø, MA (2019, May). Darcy-Scale Simulation of Boundary-Condition Effects During Capillary-Dominated Flow in High-Permeability Systems. *SPE Reservoir Evaluation & Engineering*, **22**(2), 673-691. https://doi.org/10.2118/188625-PA
2. Berawala, DS, Andersen, PØ, Ursin, JR (2019, Apr). Controlling Parameters during Continuum Flow in Shale Gas Production: A Fracture- Matrix Modelling Approach. *SPE Journal* (preprint). https://doi.org/10.2118/190843-PA
3. Andersen, PØ (2019, Mar). A simplified modelling approach for petroleum recovery by spontaneous imbibition in naturally fractured reservoirs. *Journal of Natural Gas Science and Engineering*, **63**, 95-114. https://doi.org/10.1016/j.jngse.2019.01.012
4. Andersen, PØ, Qiao, Y, Standnes, DC, Evje, S (2019, Feb). Co-current Spontaneous Imbibition in Porous Media with the Dynamics of Viscous Coupling and Capillary Back Pressure. *SPE Journal*, **24**(1), 158-177. https://doi.org/10.2118/190267-PA
5. Andersen, PØ, Lohne, A, Stavland, A, Hiorth, A, Brattekås, B (2019, Feb). Core Scale Modeling of Polymer Gel Dehydration by Spontaneous Imbibition. *SPE Journal* (preprint). https://doi.org/10.2118/190189-PA
6. Minde, MW, Wang, W, Madland, MW, Zimmermann, U, Korsnes, RI, Bertolino, SRA, Andersen, PØ, (2018, Oct). Temperature effects on rock engineering properties and rock-fluid chemistry in opal-CT-bearing chalk. *Journal of Petroleum Science and Engineering*,

169, 454-470. https://doi.org/10.1016/j.petrol.2018.05.072

7. Qiao, Y, Andersen, PØ, Evje, S, Standnes, DC (2018, Feb). A Mixture Theory Approach to Model Co- and Counter-Current Two-Phase Flow in Porous Media Accounting for Viscous Coupling. *Advances in Water Resources*, **112**, 170-188, https://doi.org/10.1016/j.advwatres.2017.12.016
8. Andersen, PØ, Wang, W, Madland, MV, Zimmermann, U, Korsnes, RI, Bertolino, SRA, Minde, MW, Schulz, B, Gilbricht, S (2018, Jan). Comparative Study of Five Outcrop Chalks Flooded at Reservoir Conditions: Chemo-Mechanical Behavior and Profiles of Compositional Alteration. *Transport in Porous Media*, **121**(1), 135-181, https://doi.org/10.1007/s11242-017-0953-6
9. Andersen, PØ, Evje, S, Hiorth, A (2017, Oct). Modelling of Spontaneous Imbibition Experiments with Porous Disc - On the Validity of Exponential Prediction. *SPE Journal*, **22**(5), 1326-1337, https://doi.org/10.2118/186094-PA
10. Standnes, DC, Evje, S, Andersen, PØ (2017, Sep). A Novel Relative Permeability Model Based on Mixture Theory Approach Accounting for Solid–Fluid and Fluid–Fluid Interactions. *Transport in Porous Media*, **119**(3), 707-738., https://doi.org/10.1007/s11242-017-0907-z
11. Andersen, PØ, Skjæveland, SM, Standnes, DC (2017, Aug). An Analytical Model for Analysis of Capillary Pressure Measurements by Centrifuge. *Petrophysics*, **58**(4):366-375.
12. Andersen, PØ, Standnes, DC, Skjæveland, SM (2017, Aug). Water flooding oil-saturated core samples - Analytical solutions for steady-state capillary end effects and correction of residual saturation. *Journal of Petroleum Science and Engineering*, **157**,364-379, https://doi.org/10.1016/j.petrol.2017.07.027
13. Standnes, DC, Andersen, PØ (2017, Jun). Analysis of the Impact of Fluid Viscosities on the Rate of Counter-Current Spontaneous Imbibition. *Energy & Fuels*, **31**(7), 6928-6940, https://doi.org/10.1021/acs.energyfuels.7b00863
14. Andersen, PØ, Evje, S (2016, May). A Model for Reactive Flow in Fractured Porous Media. *Chemical Engineering Science*, **145**, 196-213, https://doi.org/10.1016/j.ces.2016.02.008
15. Andersen, PØ, Evje, S, Kleppe, H, Skjæveland, SM (2015, Dec). A Model for Wettability Alteration in Fractured Reservoirs. *SPE Journal*, 20(6), 1261-1275., https://doi.org/10.2118/174555-PA

Conference papers

1. Andersen, PØ, Berawala, DS (2018, Oct). Analytical and Numerical Solutions for Interpretation of Chemical Compaction in Chalk. SPE APOGCE, Brisbane, Australia. https://doi.org/10.2118/192018-MS
2. Andersen, PØ (2018, Oct). Capillary Pressure Effects on Estimating the EOR Potential during Low Salinity and Smart Water Flooding. SPE APOGCE, Brisbane, Australia. https://doi.org/10.2118/191974-MS
3. Berawala, DS, Andersen, PØ, Ursin, JR (2018, Jun). Controlling Parameters for Shale Gas Production Into a Well-Induced Fracture: A Fracture-Matrix Modelling Approach. SPE EUROPEC, Copenhagen, Denmark. https://doi.org/10.2118/190843-MS
4. Andersen, PØ, Lohne, A, Stavland, A, Hiorth, A, Brattekås, B (2018, Apr). Core Scale Simulation of Spontaneous Solvent Imbibition from HPAM Gel. SPE IOR, Tulsa, Oklahoma,

US. https://doi.org/10.2118/190189-MS
5. Andersen, PØ, Qiao, Y, Standnes, DC, Evje, S (2018, Apr). Co-Current Spontaneous Imbibition in Porous Media with the Dynamics of Viscous Coupling and Capillary Back Pressure. SPE IOR, Tulsa, Oklahoma, US. https://doi.org/10.2118/190267-MS
6. Andersen, PØ, Brattekås, B, Walrond, K, Aisyah, DS, Nødland, O, Lohne, A, Haugland, H, Føyen, TL, Fernø, MA (2017, Nov). Numerical Interpretation of Laboratory Spontaneous Imbibition - Incorporation of the Capillary Back Pressure and How it Affects SCAL. SPE ADIPEC, Abu Dhabi, UAE. https://doi.org/10.2118/188625-MS
7. Andersen, PØ, Skjæveland, SM, Standnes, DC (2017, Nov). A Novel Bounded Capillary Pressure Correlation with Application to Both Mixed and Strongly Wetted Porous Media. SPE ADIPEC, Abu Dhabi, UAE. https://doi.org/10.2118/188291-MS
8. Andersen, PØ, Skjæveland, SM, Standnes, DC (2017, Apr). An Analytical Model for Analysis of Centrifuge Capillary Pressure Experiments. EAGE IOR 2017, Stavanger, Norway, https://doi.org/10.3997/2214-4609.201700304
9. Andersen, PØ, Qiao, Y, Evje, S, Standnes, DC (2017, Apr). Improved Modelling of Gravity-Aided Spontaneous Imbibition Using Momentum-Equation-Based Relative Permeabilities. EAGE IOR 2017, Stavanger, Norway. https://doi.org/10.3997/2214-4609.201700303
10. Standnes, DC, Evje, S, Andersen, PØ (2016, Aug). A novel relative permeability model – A two-fluid approach accounting for solid-fluid and fluid-fluid interactions. SCA Symposium, Snow Mass, Colorado, US.
11. Andersen, PØ, Evje, S, Ahsan, R, Hiorth, A (2015, Apr). An Analytical Model for Imbibition Experiments with Porous Plate. EAGE IOR 2015, Dresden, Germany. https://doi.org/10.3997/2214-4609.201412112
12. Nermoen, A, Korsnes, RI, Hildebrand-Habel, T, Zimmermann, U, Bollhorn, P, Christensen, HF, Agergaard, FA, Trads, N, Pedersen, J, Jettestuen, E, Vinningland, JL, Evje, S, Andersen, PØ, Hiorth, A, Madland, MV (2014, Oct). JCR-7 Symposium, France.

Conference abstracts (not full papers)

1. Andersen, Pål Østebø; Qiao, Yangyang; Evje, Steinar; Standnes, Dag Chun. Improved modeling of gravity-aided spontaneous imbibition using momentum-equation-based relative permeabilities. Interpore - 9th International Conference on Porous Media & Annual Meeting; 2017-05-08 - 2017-05-11 UIS
2. Nygård, Jan Inge; Walrond, Kenny; Andersen, Pål Østebø. Simulation Study of Miscible WAG Injection in a Stratified Model Reservoir. SPWLA International Student Paper Contest, part of SPWLA Annual Symposium; 2017-06-17 - 2017-06-21 UIS

Master theses

1. Ceballos, Anibal; Lohne, Arild (2018) Simulation of Oil Recovery Process – Co-current Spontaneous Imbibition in Fractured Reservoirs. Universitetet i Stavanger
2. Vasquez, Eliana (2018) Relative Permeability and Capillary Pressure Estimation from Core-flooding Experiments studying Capillary End Effects. Universitetet i Stavanger
3. Baig, Mirza Hassan; Nermoen, Anders (2018) Digital Image Analysis for Petrophysical Evaluation. Universitetet i Stavanger
4. Sandvik, Siri; Lohne, Arild (2018) Simulation of oil recovery by wettability alteration –

interpretation of Smart water imbibition experiments at reservoir conditions. Universitetet i Stavanger

5. Linevyuk, Nataliya (2018) Simulation study of co-current spontaneous imbibition.
6. Nergård, Kenneth (2018) Investigation of Geomechanical Effects and Other Controlling Parameters on Shale Gas Production. Universitetet i Stavanger
7. Nainggolan, Citra (2018) Core Flooding for Analysis of Capillary End Effect and Multiphase Flow Properties. Universitetet i Stavanger
8. Dixit, Aditya; Shapiro, Alexander (2018) Simulation of core scale Experiments - improved interpretation of steady state relative permeability measurements. Danmarks Tekniske Universitet, DTU
9. Aisyah, Daisy Siti. Modelling of co-current spontaneous imbibition – improved understanding of reservoir flow physics. Universitetet i Stavanger 2017 101 s. UIS
10. Gebreselassie, Eyasu. The Role of Polymer Size Distribution During Injection into a Low permeable Chalk - Numerical Simulations and Interpretation of Experimental Data. Universitetet i Stavanger 2017 51 s. IRIS UIS
11. Yosif, Malik. Polymer EOR in Fractured Chalk Reservoirs - A Simulation Study with Relevance to the Norwegian Continental Shelf. Universitetet i Stavanger 2017 85 s. IRIS UIS
12. Chunlei, Zhang. A Study of Interplay Between Capillary and Gravitational Forces with Application to Oil Recovery in Naturally Fractured Reservoirs. Universitetet i Stavanger 2016 59 s. UIS

Presentations and posters

1. Nygård, JI, Andersen, PØ (2018, Nov). Scaling of recovery during immiscible WAG injection. IER Research Day, Stavanger, Norway.
2. Andersen, PØ, Berawala, DS (2018, Nov). Analytical and Numerical Modelling of Chemical Compaction in Chalk. Lunch & Learn, IER, UiS.
3. Berawala, DS, Andersen, PØ, Ursin, JR (2018, Sep). Controlling Parameters for Shale Gas Production: A Fracture- Matrix Modelling Approach. Lunch & Learn, IER, UiS.
4. Andersen, PØ, Walrond, K, Vasquez, E, Nainggolan, C, Askarinezhad, R, Standnes, DC, Skjæveland, SM, Fjelde, I (2018, Sep). Experimental and simulation interpretation of capillary pressure and relative permeability from waterflooding experiments. IEA-EOR 2018, Copenhagen, Denmark.
5. Agista, MN, Andersen, PØ, Yu, Z (2018, Apr). Simulation Interpretation of Laboratory Nanofluid Injection in Porous Media. IOR NORWAY 2018, Stavanger, Norway.
6. Baig, MH, Nermoen, A, Nadeau, PH, Andersen, PØ, Austvoll, I (2018, Apr). Digital Image Analysis of Thin Sections for Petrophysical Properties. FORCE Seminar, Stavanger, Norway.
7. Baig, MH, Nermoen, A, Nadeau, PH, Andersen, PØ, Austvoll, I (2018, Apr). Petrographic Properties Evaluation by Digital Image Analysis of Thin Sections. IOR NORWAY 2018, Stavanger, Norway.
8. Berawala, DS, Andersen, PØ, Ursin, JR (2018, Apr). Modelling of CO2 Injection in Shale Gas Reservoirs - Improved Recovery and CCS. IOR NORWAY 2018, Stavanger, Norway.
9. Brattekås, B, Lohne, A, Andersen, PØ (2018, Apr). Core Scale EME for IOR: Experiment-Modelling-Experiment. IOR Norway 2018, Stavanger, Norway.

10. Dixit, A, Andersen, PØ, Standnes, DC, Shapiro, A, Skjæveland, SM, Walrond, K (2018, Apr). Interpretation Of steady State Relative Permeability Measurements on Composite Cores with End Effects. IOR NORWAY 2018, Stavanger, Norway.
11. Esquivel, K, Andersen, PØ, Berawala, DS (2018, Apr). Interpretation of Reactive Flow and its Impact on Compaction in Chalk. IOR NORWAY 2018, Stavanger, Norway.
12. Kallesten, EI, Madland, MV, Korsnes, RI, Zimmermann, U, Andersen, PØ (2018, Apr). Permeability and Stress State. IOR NORWAY 2018, Stavanger, Norway.
13. Nygård, JI, Walrond, K, Andersen, PØ (2018, Apr). Controlling Parameters During WAG Injection – A Simulation Study. IOR NORWAY 2018, Stavanger, Norway.
14. Andersen, PØ, Lohne, A, Stavland, A, Hiorth, A, Brattekås, B (2018, Mar). Core Scale Simulation of Spontaneous Solvent Imbibition from HPAM Gel. Lunch & Learn, IER, UiS.
15. Andersen, PØ, Walrond, K, Nainggolan, C, Vasquez, E, Askarinezhad, R, Standnes, D, Skjæveland, SM, Fjelde, I (2018, Feb). Capillary Pressure from Core Flooding. SPE Research Night, Stavanger, Norway.
16. Berawala, DS, Andersen, PØ, Ursin, JR (2018, Feb). Modelling of CO2 Injection in Shale Reservoirs. SPE Research Night, Stavanger, Norway.
17. Nygård, JI, Walrond, K, Andersen, PØ (2018, Feb). Controlling parameters during WAG injection – A simulation study. SPE Research Night, Stavanger, Norway.
18. Nygård, JI, Walrond, K, Andersen, PØ (2017, Jun). Simulation Study of Miscible WAG Injection in a Stratified Model Reservoir. SPWLA International Student Paper Contest, part of SPWLA Annual Symposium, Oklahoma City, Oklahoma, US.
19. Andersen, PØ, Qiao, Y, Evje, S, Standnes, DC (2017, May). Improved modeling of gravity-aided spontaneous imbibition using momentum-equation-based relative permeabilities. Interpore - 9th International Conference on Porous Media & Annual Meeting, Rotterdam, Netherlands.
20. Andersen, PØ, Standnes, DC, Skjæveland, SM (2017, May). Capillary End Effects during Core Flooding – Analytical Solutions and Capillary Numbers accounting for Saturation Functions. Lunch & Learn, IPT, UiS.
21. Andersen, PØ (2016, Dec). Modelling of Imbibition Tests with Porous Disc – The Validity of Exponential Models. Lunch & Learn, IPT, UiS.
22. Andersen, PØ, Evje, S (2016, Jun). Fracture-Matrix Models for Reactive Flow in Naturally Fractured Formations. Lunch & Learn, IPT, UiS.