The National IOR Centre of Norway

Post Doc report (Trine Solberg Mykkeltvedt), part of

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

Project 2.6.1

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Project duration: November 2014 – December 2018

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PhD students and postdocs: Trine Solberg Mykkeltvedt (postdoc)

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1. Executive summary

This report summarises the research work performed by postdoc Trine Solberg Mykkeltvedt as part of the IOR centre task Reservoir simulation tools. The report covers the period November 2014-September 2019 (including two breaks for maternity leaves).

The main focus of the work has been numerical simulation of the water-based EOR method Polymer flooding, using higher-order methods. In particular, how to reduce numerical diffusion while still keeping the computational cost of the simulation at a reasonable level. The work has resulted in three journal papers and two conference papers, in addition to several conference and workshop presentations.

A second objective of this work has been to study convection in the context of CO_2 injection for EOR. Extensions of the OPM flow simulator has been done, we have improved and tested the compositional framework for EOR-CO_2 simulations and done subsequent research on CO_2 injection for EOR.

Use of higher-order spatial discretization schemes have been proposed by many authors as a means to reduce numerical diffusion and grid-orientation effects. Most higher-order simulators reported in the literature are based on explicit time stepping, and only a few are implicit. One reason that fully implicit formulations are not widely used might be that it becomes

quite complicates to compute the necessary linearizations for modern high-resolution discretizations of total variation diminishing (TVD) and weighted essentially non-oscillatory (WENO) type. Herein, we solve this problem by using automatic differentiation. We also demonstrate that using lagged evaluation of slope limiters and WENO weights alleviates the nonlinearity of the discrete systems and improves the computational efficiency, without having an adverse effect on the stability and accuracy of the higher-resolution schemes.

As an example of EOR, we consider polymer flooding, which involves complex and adverse phenomena like adsorption in the rock, degradation and in-situ chemical reactions, shear thinning/thickening, dead pore space, etc. The transport of polymer is largely linear and thus highly affected by numerical diffusion. This displacement process is complex and challenging to simulate, and the polymer fronts will in the worst case be linear waves that have significantly less self-sharpening effects than water fronts. Thus, this application is a good example of a situation where higher-order methods could improve the simulation significantly.

First, using a few idealized test cases in [1,4], we compare explicit and fully implicit time stepping for a variety of high and low-resolution spatial discretizations. Next, in [2, 5] we study the use of second- order WENO applied to polymer flooding on unstructured grids and show that using a second-order reconstruction will reduce the numerical dissipation without compromising significantly on the computational cost. In addition, we have studied CO_2 injection for EOR using the OPM simulator. The interaction between existing oil and injected CO_2 needs to be fully understood to effectively manage CO_2 migration and storage efficiency. When CO_2 and oil mix in a fully miscible setting, the density can change non-linearly and cause density instabilities. These instabilities involve complex convective-diffusive processes, which are hard to model and simulate. In [3] we demonstrate that convection occurs rapidly, and has a strong effect on breakthrough of CO_2 at the outlet. This work for the first time quantifies these effects for a simple system under realistic conditions. Furthermore, from this work we have highlighted many interesting research questions that hopefully will be further developed and targeted in future projects. Note that the research in paper [3] has been in close collaboration with the NFR projects 268439 (UNCOVER) and 255510 (Chi).

2. Introduction and background

Reservoir simulation is a complementary tool to field observations, laboratory tests, and analytical models. The goal of these simulations is to provide a database that can help oil companies to position and manage wells to maximise the oil and gas recovery. These tools can sometimes be invaluable to improve oil recovery, and it is important to advance the state-of-the-art of modeling and simulation in the context of reservoirs.

Most reservoir simulators use schemes that are only first-order accurate, and may cause high viscosity effects. In water-based EOR methods the physical properties of the fluids and the surrounding rock can be modified through active chemical or biological substances. The transport of these substances is largely linear and therefore highly affected by numerical diffusion. Furthermore, the subsequent effects on the fluids and the surrounding rock are highly nonlinear and sensitive to threshold parameters that determine transitions between regions of very different behaviour. Thus, the displacement process is complex and challenging to simulate. Unresolved simulation can lead to misleading predictions of injectivity and recovery profiles.

It is well known that higher-order schemes provide a better resolution and reduce the smoothing near discontinuities in the solution. These schemes are in general at least second-order accurate on smooth parts of the solutions and give well resolved non-oscillatory solutions near discontinuities. However, these schemes can be difficult to implement and are often computationally expensive. In this work, the application of such schemes has been studied for polymer flooding as an example of a water-based EOR method that is challenging to simulate accurately.

Carbon-neutral oil production is one way to improve the sustainability of petroleum resources. The emissions from produced hydrocarbons can be offset by injecting capture CO_2 from a nearby point source into a saline aquifer for storage or a producing oil reservoir. The injected CO_2 will interact with the oil and cause it to flow more freely within the reservoir. The interaction between existing oil and injected CO_2 needs to be fully understood to effectively manage CO_2 migration and storage efficiency. In this work, we study this interaction to better understand the underlying processes.

The research topics were chosen based on the submitted proposal for the IOR centre, the roadmap, and feedback along the project period. The project delivers to the category Upscaling, simulation and interpretation tools and Monitoring tools and history matching (by providing a tailor made forward simulator). In the end, the project contributes to pilot simulations by providing a full field simulation tool for water based IEOR methods. Developing reservoir simulation tools contributes to milestone 8, and helps to achieve Milestone 9 (full field history matching) as a reliable forward simulator is an important step in history matching study. The project also delivers to the milestone 12, the tool-box for interpretation of pilot-tests, as numerical simulations are an essential part of pilot tests.

The project has mainly developed through a collaboration with Knut-Andreas Lie (SINTEF Digital), Xavier Raynaud (SINTEF Digital), Olav Møyner (SINTEF Digital) and Sarah E. Gasda (NORCE). The project is also linked to the PhD project of Anna Kvashchuk (UiS) under supervision of Robert Klöfkorn (NORCE) in the same task, and has also collaborated with the developers of the Open Porous Media (OPM) project represented by Tor Harald Sandve (NORCE). The numerical methods studied herein have been integrated in OPM.

3. Results

In the papers [1,4] we use a few idealized test cases to compare and contrast explicit and fully-implicit time stepping for a variety of high and low-resolution spatial discretizations applied to polymer flooding. We found that it is (relatively) simple to implement such schemes using automatic differentiation and that the resulting schemes work well with standard techniques for time-step control. We also presented a simple illustrative case, as well as several numerical experiments, that all demonstrate that implicit time discretizations are more suitable than explicit time integration. High computation cost is key argument against the use of higher-resolution discretizations as part of a fully implicit formulation. To make these methods amenable for realistic flow scenarios, we found that preference should be given to spatial stencils and nonlinear limiter functions that are as smooth as possible to avoid exacerbating the nonlinearity of the implicit flow equations.

We found that the use of a high-resolution spatial stencil improves the accuracy both for smooth and discontinuous parts of the solution and reduces grid-orientation effects. As a simple rule of thumb, the second-order scheme provides (at least) as good resolution as we would get from the first-order scheme on a 2 x 2 refined grid with twice as many time steps. To assess how grid-orientation-errors are affected by different higher-order schemes, we compared solutions computed using a quarter five-spot and a rotated five-spot setup. We found that using a second-order scheme counteracts these grid-orientation errors in the sense that the solutions are almost identical for the original and rotated computational setups.

In [1] we also extend the work of [4] by demonstrating that using lagged evaluation of slope limiters or WENO weights in the higher-order reconstructions not only improves the iteration count of the nonlinear solver, while retaining the accuracy and stability of the original scheme, but also leads to a pronounced reduction in the computational cost of the automatic differentiation used for linearization. This is an important practical step toward utilization of fully implicit high-resolution schemes for contemporary simulation models of real reservoirs.

To what extent the observations in [1, 4] carry over to more realistic 3D cases with strongly heterogeneous geology represented on grids with non-Cartesian cell geometries and complex topology was still an open question. For this reason, in [2, 5] we studied the use of second-order WENO on unstructured grids. We propose a second-order WENO discretization suitable for complex grids with polyhedral cell geometries, unstructured topologies, large aspect ratios, and large variations in interface areas. The WENO scheme is developed as part of a standard, fully implicit formulation that solves for pressure and transported quantities simultaneously. We investigate the accuracy and utility of the WENO scheme for a series of test cases that involve corner-point and 2D/3D Voronoi grids and black-oil and compositional flow models.

In paper [3] we study we simulate gravity effects, namely gravity override and convective mixing, during miscible displacement of CO_2 and oil. The flow behavior due to the competition between viscous and gravity effects is complex due to non-monotonic density off the mixed fluids, and can only be accurately simulated with a very fine grid. We demonstrate and find that under a range of conditions convection occurs rapidly, and has a strong effect on breakthrough of CO_2 at the outlet. Furthermore, CO_2 with convection can enhance the vertical sweep of the reservoir and lead to more efficient displacement process. Especially, these effects are quantified for a simple system under realistic conditions.

4. Conclusion(s)

In the papers [1,4] we found that the use of a high-resolution spatial stencil improves the accuracy both for smooth and discontinuous parts of the solution and reduces grid-orientation effects. The results also show that preference should be given to spatial stencils and nonlinear limiter functions that are as smooth as possible to avoid exacerbating the nonlinearity of the implicit flow equations.

In papers [2,5] we have presented the formulation of a fully implicit WENO scheme, which is applicable to black-oil type and compositional simulations, and discuss some special adaptations necessary to obtain an efficient and robust scheme on the types of grids found in contemporary reservoir models. A series of numerical tests show that the WENO scheme improves the resolution of both linear and nonlinear waves significantly, typically giving the same resolution as the standard SPU scheme with twice as many grid cells in each spatial direction or ten times as many time steps.

The computational cost of WENO is higher than SPU, not only because of the reconstruction procedure and the denser local stencil, which incurs more evaluations of partial derivatives, but also because the scheme requires more iterations. In [1], we also discussed lagged evaluation of the nonlinear weights to reduce the nonlinearity of the discrete stencil. Lagging the evaluation over the whole time step seems to work well for imbibition or drainage processes with monotone displacement profiles, but breaks down almost immediately in water-alternating-gas (WAG) type scenarios. Lagging the evaluation in the nonlinear iteration process does not seem to cause similar breakdown, but has little effect on the computational efficiency. We believe a better approach would be to localize reconstruction to regions with significant fluid movement and try to reuse previous nonlinear weights for stencils where changes in cell averages are below a prescribed value. This requires more research.

In [3] we study CO_2 injection in an oil filled reservoir, and demonstrate that convection occurs rapidly, and has a strong effect on breakthrough of CO_2 at the outlet. This work for the first time quantifies these effects for a simple system under realistic conditions. Increased efficiency is positive for increasing storage of CO2 behind the oil front and maximising the ratio of CO_2 stored per oil produced. We emphasise that the knowledge about the effect of convective mixing on the field scale is limited. This is something the research community needs to focus more on, and the work done in [3] is a starting point to decrease this knowledge gap.

6. Dissimination of results

Journal papers

1. Mykkeltvedt, Trine S.; Raynaud, Xavier; Lie, Knut-Andreas: *Fully implicit higher-order schemes applied to polymer flooding.* Computational Geosciences **21**, 1245-1266 (2017)

2. Lie, Knut-Andreas; Mykkeltvedt, Trine S.; Møyner, Olav: *Fully implicit WENO scheme on stratigraphic and unstructured polyhedral grids.* Computational Geosciences **24 (2)**,

405-423 (2020)

3. Mykkeltvedt, Trine S.; Gasda, Sarah E.; Sandve, Tor H.: *CO_2 convection in hydrocarbon under flowing conditions.* Transport in Porous Media **139** 155170 (2021)

Conference papers

4. Lie, Knut-Andreas; Mykkeltvedt, Trine S.; Raynaud, Xavier: *Fully implicit higher-order schemes applied to polymer flooding.* ECMOR XV - Proceedings of 15th European Conference on the Mathematics of Oil Recovery, Amsterdam, Netherlands, 29 August - 1 September, (2016)
5. Lie, Knut-Andreas; Mykkeltvedt, Trine S.; Møyner Olav: *Fully implicit WENO schemes on stratigraphic and fully unstructured grids.* ECMOR XVI - Proceedings of 16th European Conference on the Mathematics of Oil Recovery, Barcelona, Spain, 3 - 6 September, (2018)

Presentations and posters

6. Mykkeltvedt, Trine S.; Lie, Knut-Andreas; Raynaud, Xavier: *Fully implicit higher-order schemes applied to polymer flooding.* ECMOR XV; 2016-08-28 - 2016-09-02
7. Lie, Knut-Andreas; Mykkeltvedt, Trine S.; Møyner, Olav: *Fully implicit higher-order schemes applied to polymer flooding.* Computational Issues in Oil Field Applications – Workshop I: Multiphysics, Multiscale, and Coupled Problems in Subsurface Physics; 2017-04-03 - 2017-04-07
8. Mykkeltvedt, Trine S.; Lie, Knut-Andreas; Raynaud, Xavier: *Simulating polymer flooding using implicit high-resolution methods.* SIAM GS 2017; 2017-09-10 - 2017-09-14
9. Lie, Knut-Andreas; Mykkeltvedt, Trine S.; Møyner Olav: *Fully implicit WENO schemes on stratigraphic and fully unstructured grids.* ECMOR XVI; 2018-09-03 - 2018-09-06
10. Mykkeltvedt, Trine S.; Sandve, Tor H.; Gasda, Sarah. E.; Aavatsmark, Ivar: *Mixing of CO2 and oil in a CO2-EOR reservoir.* IOR Norway 2019; 2019-03-19 - 2019-03-20
11. Mykkeltvedt, Trine S.; Sandve, Tor H.; Gasda, Sarah .E.; *Simulation technology for carbon negative oil production.* Bergen CCUS Seminar 2019 -12 -03
12. Mykkeltvedt, Trine S.; *CCS: når fornybar energi ikkje er nok.* Energiomstilling NÅ! Bergen 2019 - 11 - 21

13. Gasda, Sarah E.; Mykkeltvedt, Trine S.; Sandve, Tor H.; Aavatsmark, Ivar; Elenius, Maria; *The role of convection for CO_2 migration and trapping in CO_2-EOR Reservoirs.* Interpore 2019; 2019-05-06 - 2019-05-10

14. Gasda, Sarah E.; Mykkeltvedt, Trine S.; Sandve, Tor H.; Aavatsmark; *Permanent carbon storage in EOR reservoirs: towards carbon-neutral hydrocarbon production on the NCS.* IOR Norway 2019; 2019-03-19 - 2019-03-20