PROJECT MICAP: FINAL REPORT

CLIMIT PROJECT 268390: EFFICIENT MODELS FOR MICROBIALLY INDUCED CALCITE PRECIPITATION AS A SEAL FOR CO_2 STORAGE

OBJECTIVES

The primary project objective is to develop and verify robust and efficient simulation tools for microbially induced calcite precipitation (MICP) to gain improved understanding of mechanisms and strategies that prevent leakage of CO_2. The secondary objectives are to:

- develop upscaled models that describe MICP processes at the field scale
- develop stable and converging numerical methods to solve the upscaled models with small splitting errors and controlled stiffness
- suggest injection strategies that provide lateral sealing of the caprock/aquifer interface, while keeping high injectivity for CO_2 injection

BACKGROUND

A major concern with geological carbon capture and storage (CCS) is leakage out of the storage formation through fractures developing in the caprock or through open/reactivated faults. Although a storage site is extensively studied before and during CO_2 injection to avoid leakage paths to develop, storage operators are obligated to take corrective measures in case a significant leakage occurs. Furthermore, the public acceptance of CO_2 storage in some countries is low due to fear of leakage. Thus, it is important to develop safe and efficient technology for sealing CO_2 leakage paths.

Several sealing solutions have been suggested in the literature, from polymeric gel to creating a hydraulic barrier. In this project, we study a biochemical technology – microbially induced calcite precipitation (MICP). The fundamental idea behind MICP is use bacteria to catalyze the production of calcium carbonate – calcite – from urea and calcium. Calcite is a low-permeable mineral that act as the sealing agent by decreasing pore space and thereby decreasing porosity and permeability. Over the years, MICP have been extensively studied in pore- and core-scale laboratory experiments to understand the fundamental processes, with a few large-/field-scale proof-of-concept demonstrations.

Numerical simulation tools developed for MICP have mainly focused on reproducing pore- and core-scale experiments. The challenges in modeling MICP are the coupled processes, many which are not fully understood, and the different spatial and temporal scales of the processes. To apply MICP on field-scale problems, like CO_2 storage, robust and efficient numerical simulation tools are needed. With reliable numerical tools, we can study important aspects of leakage sealing with MICP such as optimal injection strategies.

PROJECT RESULTS

In Phase 1 of the project, the focus was on developing a simulation model to study and show the potential of MICP as a leakage sealing technology on field scale. To have a solid foundation for field-scale simulations, we first conducted a thorough literature study on the important microbial aspects of bacterial transport in porous media. The results from the study showed that the widely used bacteria, *Sporosarcina Pasteurii*, is ideal for large-scale application in CO_2 storage sites. Furthermore, we developed two injection approaches with associated mathematical and numerical models: (I) inject pre-cultivated bacteria and cementation solution for calcite precipitation from suspended bacteria; and (II) inject bacteria, growth solution, and cementation solution to cultivate biofilm and subsequent calcite precipitation from the biofilm. In both approaches, we reduced and simplified the involved processes to only approximate the most important ones based on microbial considerations and previous mathematical/numerical models. Simulation studies with both injection strategies clearly showed the potential for MICP as a field-scale leakage sealing technology, with injection approach (II) achieving the most significant decrease in porosity and permeability.

Based on the results from Phase 1 of the project, we continued in Phase 2 with development of the simulation model for injection approach (II), making it the main focus for the Post-doc position. The model was implemented in the open-source simulator Matlab Reservoir Simulation Toolbox (MRST), with several improvements over the model in Phase 1, such as dispersion effects and an improved porosity-permeability function. An important practical problem for field-scale application of MICP is the injection strategy, that is, when and at what rate to inject the involved components. Based on learnings from laboratory experiments and numerical studies, we suggested an injection strategy consisting of separate injection of microbial, growth, and cementation solutions with no-flow periods in-between to maximize retention times and minimize clogging in unwanted locations. We conducted several 1D and 2D simulation studies to investigate different aspects of the MICP dynamics on field scale. Learnings from each study were applied to the ultimate test of running MICP simulations on a well-known 3D CO_2 benchmark problem with an explicitly modeled leakage path. The results showed that we effectively closed the leakage path, further proving the potential of the MICP technology.

The MICP model used for the simulation studies has been made available as a part of the official MRST release as of 2021b (module `ad-micp`). Since MRST is primarily a research tool for rapid prototyping, we decided to implement the simulation model in the Open Porous Media (OPM) Flow simulator. OPM Flow is a fully implicit, open-source simulator capable of running industry-standard models. Through considerable efforts, the MICP model was made part of the official OPM Flow release as of version 2021.10. In a study, we showed good agreement between both implementations with OPM Flow providing by far the shortest simulation times. We have also developed an open-source Python package, `py-micp`, to enable MICP studies and subsequent CO_2 leakage assessments.

A key objective of the project was to study coupled flow and reactive transport problems and the interaction of processes with the subsurface geometry, such as fractures. We investigated a fracture of small width in an equal dimensional model coupled to the flow in the matrix and performed an upscaling of the Richards equation, a non-linear flow model. The results show that there is a hierarchy of fracture flow models depending upon the permeability and porosity of the fracture. We have also performed a rigorous derivation of the upscaling process in certain regimes of permeability and porosity scaling. Moreover, the methodology developed has been used to obtain similar fracture flow models for several different contexts including multiphase flow polymer enhanced oil recovery.

A fundamental question in this project is the effect of geometry changes at the pore scale. The prominent geometry changes in MICP are permeability and porosity changes due to the biochemical reactions associated with calcite precipitation. For the simulations at the field scale, typically porosity-permeability relationships (e.g., Karman-Kozeny relationship) are used. However, these are ad hoc models where it is assumed that the relationship is monotone. We have justified, using mathematical arguments, that these changes in the permeability and porosity are monotone with respect to the geometric changes. Moreover, we have extended this to study the continuity of effective permeability and diffusion tensors due to geometry changes. Lastly, we have also obtained results regarding the variation of the eigenvectors of these tensors due to precipitation-dissolution reactions; a joint work with Prof. Willi Jäger, Univeristy of Heidelberg (Germany).

To seal leakage paths, possibly several tens-of-meters away from the injection well using MICP requires optimization of the injection strategy. Control variables like injection rate and periods need to be tuned in such a way that maximum calcite precipitation occurs at the leakage location, with minimal influence on the rest of the reservoir. Additionally, several of the processes involved in MICP have been determined in laboratory experiments that are mostly not carried out under reservoir conditions and are thus associated with large uncertainty. We developed an optimization framework to find optimal control variables that are valid regardless of model uncertainty. We also included the ability to adjust the risk attitude, e.g., towards unnecessary calcite precipitation in the reservoir. The optimization framework used a surrogate model to reduce the computational cost of simulations and an efficient Monte Carlo method to reduce the number of samples needed. Numerical studies demonstrated the capabilities of the optimization framework along with the accuracy of the surrogate model and efficiency of the Monte Carlo method.

We developed an additional optimization procedure (without including model uncertainty) to focus on optimal injection strategies for field-scale application. The MICP model implemented in OPM Flow enabled us to perform 3D case studies on systems with explicit leakage paths in order of minutes. To ensure that maximum calcite precipitation occurred at the leakage path, we developed a new injection strategy where components were injected in different parts of the well and only mix when reaching the leakage path. Furthermore, we included penalty on time spent on MICP sealing operation, consequently reducing the shutdown period of CO_2 storage activity. Results from the test cases showed that the optimization procedure was able to effectively close all leakage paths (>99.8% CO_2 leakage reduction).

During the last year of the project, we initiated a cooperation with Ass. Prof. Brian Ellis and PhD student Eva Albalghiti, both from University of Michigan (USA). With their expertise in laboratory core flooding experiments and imaging, more fundamental processes related to our MICP simulation model could be investigated. Together, we designed several core flooding experiments investigating influence of pore-size distribution on MICP induced permeability reduction. Using micro-CT scanning, porosity and permeability evolution in each core could be measured. The results showed that different types of sandstone, with different pore-size distributions, affected the permeability reduction, and the calcite precipitation pattern matters on the resilience to acidic exposure (e.g., CO_2). From this initial study, several new experiments are planned, tailored specifically to increase the understanding of field-scale MICP processes and improve our simulation model. The experiments will be conducted in several stages (some finished during MICAP project period): batch experiments to investigate bacterial processes; column stacks to measure, e.g., bacterial attachment and biofilm development; and core flooding for investigation of rock parameter impact and injection strategies.

KEY R&D TASKS AND PARTNER ROLES

In this project, we have combined approaches to advance new knowledge in three key areas: (1) developing field-scale mathematical and numerical models for MICP; (2) developing optimal injection strategies for practical application of MICP; and (3) providing numerical analysis and rigorous proof of formal upscaling methods. All research partners have played a role in the project:

NORCE has led all the main activities of the project: (1) developed and implemented a field-scale simulation model for MICP; (2) developed two optimization procedures for injection strategies using MICP; (3) led the Post-doc project contributing to (1) and (2).

UiB led the development and analysis of formal upscaling methods, and provided advising in the Post-doc project.

University of Stuttgart, Tufts University, and Wintershall DEA provided guidance to the project and collaboration.

IMPLEMENTATION AND USE OF RESOURCES

The project to date has produced: **4 peer-reviewed journal papers, 1 paper under review, 3 conference papers/extended abstracts, 1 NFR report (Phase 1), >10 presentations at conferences and lectures, and 1 Post-doc project completed**. Technical infrastructure developed in the project include **implementation in open-source simulators MRST and OPM**, and **two optimization codes**.

Due to the severe restriction from the COVID-19 pandemic, the international workshop in WP D2 could not be carried out. We planned to the last moments of the project to arrange a workshop together with the NFR

INTPART project Inspire, but that workshop was unfortunately postponed until after MICP project ended, due to reasons related to COVID-19. Most of the budget originally dedicated to organizing the workshop in WP D2 was transferred to cover Brian Ellis' contribution to the project.

ANTICIPATED SIGNIFICANCE/BENEFITS OF THE RESULTS

The MICAP project has made significant advancements in the field-scale application of MICP. By careful considerations and informed approximations, as well as numerical analysis of formal upscaling methods, we developed MICP models that capture the most important processes on the field scale. Implementing our models into an industry-standard simulator (OPM Flow) we have provided a tool for planning and management of MICP sealing operations. Moreover, due to the simulation tools being open source, any further advancements of the field-scale MICP model can easily be implemented and tested. Furthermore, the complexity of injecting several components and effectively initiating the MICP process at the leakage location have been alleviated by the development of optimization frameworks and various injection strategies in the project. By using optimal injection strategies, any MICP operation will be more cost efficient and safer. The numerical studies performed in this project have given several insights into field-scale behavior of MICP. For instance, the biological and chemical model parameters, such as bacterial attachment rate and urease production rate, have a significant impact on the MICP process, but are associated with large uncertainty from laboratory experiments. Hence, we anticipate that model parameters with large impact on field scale to be revisited in laboratory experiments, which we also initiated in the project with our cooperation with University of Michigan.

For society, the results from this project provide more confidence in a sealing technology that could be applied in the event of leakage paths developing during CO_2 sequestration. In countries where fear of CO_2 leaking to the surface, especially for onshore storage sites, showing advancements in a safe and efficient sealing technology should increase the public acceptance of CCS.

The project has trained a Post-doc researcher by further improving the skills in modeling coupled processes and implementation into simulation tools, as well as communication skills by several presentations in national and international conferences.

DISSEMINATION AND UTILIZATION OF RESULTS

Most of the publications in this project are open access, and we will strive for making the rest open access when and if possible. Results from this project will be utilized in the following manner:

- The cooperation with University of Michigan will continue beyond the end of this project. The MRST implementation of the MICP simulator will be used to compare with experimental results and inform new experiments. Several journal papers are anticipated from the cooperation.
- Preliminary investigation of MICP on carbonate fields have been done at NORCE (in cooperation with DTI). We plan to continue the investigations in a full research project is where the simulation model from MICAP will used and further developed.

ANTICIPATED RESULTS POST-COMPLETION

A paper on field-scale optimization of injection strategies using MICP has been submitted to Computational Geosciences and is currently under review. One abstract has been sent to the InterPore 2022 conference, and one abstract is currently being written for the XXIV CMWR conference.