

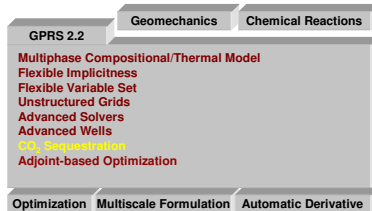
Background

Introduction

The design and monitoring of geological carbon storage operations require many key capabilities, including advanced techniques for computational modeling. The goal of this work is to develop a robust, flexible and efficient capability for such modeling and to incorporate it into Stanford's General Purpose Research Simulator (GPRS). In the past years, various capabilities relating to CO₂ sequestration have been implemented and tested in GPRS. To benchmark the numerical and physical models against other simulators, we participated in a comparative study that focused on CO₂ injection into deep saline aquifers. The results show that GPRS is indeed capable of simulating large-scale CO₂ sequestration problems in complex reservoirs with very competitive computational efficiency.

Because an important long-term storage mechanism is the mineralization of the injected CO₂, chemical equilibrium reactions have also been implemented in GPRS to model the CO₂ mineralization process.

The GPRS Research Platform



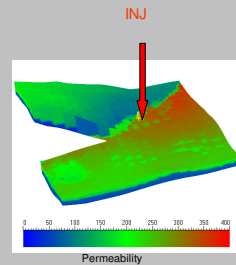
Ongoing Activities

- Scaling analysis & high-accuracy simulations of CO₂ flows
- High-order AIM (Adaptive Implicit Method) schemes
- Algebraic finite-volume multiscale formulation
- Propagation of gravity currents
- Computational optimization of sequestration operations
- Particle methods for nonlinear multiphase flow
- Modeling CO₂ mineralization reactions

GPRS Results

CO₂ Sequestration Benchmark Study

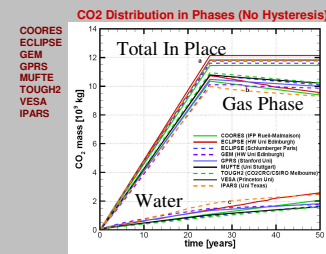
The Johansen Formation in the Troll area off the coast of Norway has been proposed as a potential CO₂ sequestration site. The study area has been extracted from the larger formation, which is approximately 100 km² in area and is situated about 3000 m below the sea floor.



The heterogeneous formation is simulated as a saline aquifer initially saturated with water. The simulation model, shown in the figure to the left, contains a fault, where the pressure is assumed to be constant. Approximately 0.47 megatons/year of CO₂ is injected near the center of the aquifer for 25 years. The well is then shut in to allow the CO₂ to migrate upwards through the formation for the next 25 years.

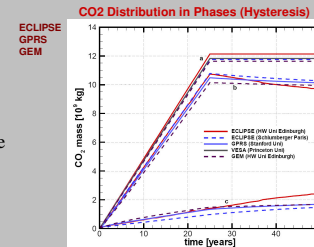
Comparison Results

A total of 13 simulators were applied by a number of independent research groups. The results below display various solutions for the mass of injected carbon dioxide in different phases.



If hysteresis is not considered, eight of the thirteen simulators yielded results that were in fairly close agreement. In particular, the total injected CO₂ results from GPRS, ECLIPSE, VESA, MUFTE, TOUGH2, and IPARS are so close that it is difficult to distinguish between them.

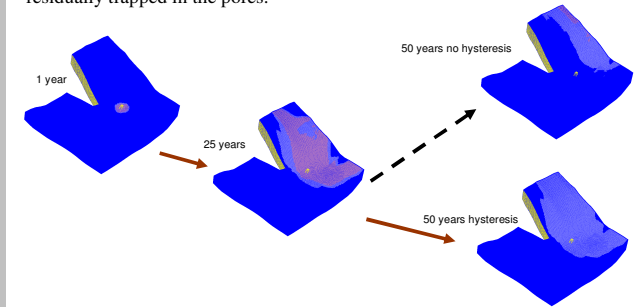
If hysteresis is included, the simulation becomes more complicated. Only four of the simulators possess the capability to simulate hysteresis. It is interesting to note that the results from GPRS fall in the middle of the curves generated by the simulators (see figure to the right).



GPRS Enhancements

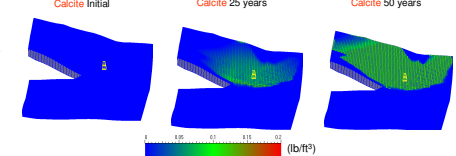
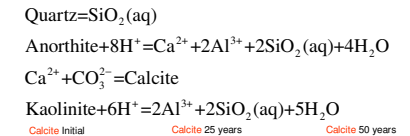
Benchmark Study Additional Results

The benchmark results demonstrate that the basic GPRS implementation provides results for CO₂ sequestration in agreement with other simulators. The following case was slightly modified from the benchmark study in order to illustrate the effect of hysteresis. We observe that, after 25 years, the top views of the CO₂ plumes are almost identical in the cases with and without hysteresis. However, after 50 years, the hysteresis effect is so significant that around 70 percent of the remaining CO₂ is residually trapped in the pores.



Preliminary CO₂ Mineralization Results

Chemical equilibrium reactions have also been implemented in GPRS. A sample case shown here extends the benchmark study. A total of four mineral reactions were included in the simulation. We observe that the calcite precipitation is quite significant.



Conclusions & Future Work

Various capabilities for CO₂ sequestration have been implemented in Stanford's General Purpose Research Simulator. A benchmark study involving a complex potential CO₂ storage reservoir has been simulated in GPRS. Results show that GPRS results matched those of other simulators in predicting the injected CO₂ distribution without considering hysteresis. In the case with hysteresis, GPRS yielded results that were very close to ECLIPSE and GEM. This close agreement provides an important benchmark for our CO₂ sequestration modeling capability. In addition, a preliminary treatment for CO₂ mineralization has been implemented in GPRS. The next step is to efficiently incorporate chemical reactions in GPRS within a general framework.