A model-oriented benchmark problem for CO$_2$ storage

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Abstract
Simulation of CO$_2$ storage in geological formations inherently involves decisions concerning relevant physics, upscaling, and numerical modeling. We propose a benchmark study designed to assess the impact of these necessary choices, within the context of storage in a conceptually simple geological formation. The benchmark asks for answers to relevant questions regarding the ultimate fate of the injected CO$_2$ plume.

1 Purpose
Geological storage of CO$_2$ remains one of the most promising options for mitigating anthropogenic release of greenhouse gases. Among the attractive features of geological storage are: Technological experience from more than 150 years of subsurface oil and gas production; vast storage capacity; and small impact on natural and environmental resources [7].

While there is a large amount of experience in multiphase flow through porous media from the petroleum community, few of the models developed there can boast significant predictive capability. Conversely, where confidence has been built in ensemble modeling in the nuclear waste disposal community (see e.g. the evaluation of the Yucca Mountain project [1], few of those models extend readily to multiphase flow, in particular at the length scales involved in significant carbon storage sites.

As a result, the carbon modeling community is faced with a new challenge in terms of model simplifications [9]. In particular, it is clear that traditional computational science methods, where the governing equations are discretized until a converged solution is obtained, will likely not be computationally feasible for this problem [2]. This has been largely acknowledged, and several simplified modeling approaches have been proposed [6, 9, 10].

The purpose of this benchmark is thus two-fold. Foremost, it aims at giving an assessment of upscaling and modeling choices applicable for the CO$_2$ storage problem. Secondly, by providing a suite of modeling approaches, all with clear support in the community, we hope to also give some indication of the uncertainty which is introduced during the stage of model adaption. As such,
we have chosen a domain and fluid properties which are highly idealized, in the hope that we may be able to isolate model uncertainty.

We invite all interested parties, and in particular participants of the workshop on numerical methods for CO$_2$ storage to be held in Svalbard, August 2009, to present their solutions to this benchmark problem. Sections 2 and 3 of this document represent the original benchmark definition, while Section 4 represents the clarifications to the benchmark introduced after the workshop was held.

2 Benchmark Definition

The benchmark properties are motivated by typical sedimentary formations.

2.1 Aquifer geometry

The aquifer is bounded by parallel impermeable confining formations above and below. We consider an aquifer dip of 1%. The aquifer thickness is 50 meters, and it extends 200 km in the dip direction, and 100 km in the direction perpendicular to dip.

2.2 Initial conditions

The center of the aquifer is situated at a depth of 2.5 km below the water table, under typical (pure) hydrostatic and geothermal conditions based on a surface temperature of 10°C and a geothermal gradient of 25°C/km.

2.3 Boundary conditions

The flow boundary conditions in the horizontal directions are constant head. We consider fixed temperature boundary conditions at the boundary of the domain.

2.4 Injection operation

A horizontal well, injecting at the bottom impermeable boundary of the formation, placed 50 km updip from the lowest point of the formation, and in the center with respect to the horizontal direction perpendicular to dip. The well length is 1 km, and the orientation is perpendicular to the dip of the formation. Injection rate is 1 Mt/y for 20 years. Infinite post-injection time period.

2.5 Formation properties

Homogeneous aquifer permeability of $10^{-13}$ m$^2$, porosity of 15%. Rock thermal conductivity of 3 W/(m·K). The formation is incompressible, with no fractures.
2.6 Fluid properties
Based on typical PTV data. Pure brine, no salt concentration.

2.7 Parameters in two-phase extension of Darcy’s law
Primary drainage relative permeability for water and for CO$_2$ by simple power
law expressions (Brooks and Corey, [3]), here given respectively by

$$k_{r,W} = S_{W,n}^4$$  \hspace{1cm} (1)

and

$$k_{r,CO_2} = 0.4(1 - S_{W,n}^2)(1 - S_{W,n})^2,$$ \hspace{1cm} (2)

where $S_{W,n}$ is the normalized water saturation where the irreducible water sat-
uration is set to $S_{cr,W} = 0.2$. The primary drainage capillary pressure (units
bar) is given by

$$P_{C,d} = 0.2S_{W,n}^{-1/2}. \hspace{1cm} (3)$$

Hysteresis may be included in both relative permeability and capillary pres-
sure description. Irreducible CO$_2$ saturation for the bounding imbibition curve
(imbibition from irreducible water saturation) is assigned the value $S_{cr,CO_2} = 0.2$. Intermediate capillary pressure and relative permeability scanning curves
may be obtained by various hysteresis models such as [4], [5] and [12]. The
irreducible CO$_2$ saturations for the scanning curves can be found by Land’s
relation [8], where Land’s constant corresponding to the bounding irreducible
saturation is 3.8.

2.8 Mineralogy
If study of mineral reactions is desired by any participating group, we suggest
to use standard Berea sandstone, and initialize the brine in equilibrium with
the rock.

2.9 Rock mechanics
Participating groups interested in including geomechanical effects should use
overburden properties consistent with the initial conditions and geomechanical
properties of the aquifer consistent with Berea sandstone.

3 Benchmark Questions
These questions should be addressed by all modeling groups.

3.1 Extent
Maximum extent of plume updip at time of injection stop, 100 years later,
and at time when all carbon is immobilized (residual saturation, dissolved, or
mineral bound).
3.2 Time
Time of immobilization of carbon; in the sense of no free phase CO$_2$.

3.3 Phase distribution
Total distribution of carbon in free phase, residual phase, dissolved state, and minerally bound at injection stop, 100 years later, and at the time when all carbon is immobilized.

3.4 Modeling approach
It is unlikely that any participating group will be able to obtain an analytical solution (or converged numerical solution) taking into account all physical and chemical processes in the system. Certain approximations must therefore be introduced, and these approximations will likely impact the answers to the benchmark questions. It is therefore paramount that each modeling group carefully details the approximations they have introduced, be it in upscaling, discretization, or treatment of physical processes.

4 Addendum, August 2009
The following modifications are introduced to the benchmark subsequent to the Svalbard workshop.

4.1 Diffusivity
CO$_2$ diffusivity in water is on the order of 1-2 $10^{-9}$ m$^2$/s [13]. With the effect of tortuosity, we prescribe a diffusion coefficient for the benchmark as simply $10^{-9}$ m$^2$/s.

4.2 Dispersion
Dispersion should be modeled using Berea sandstone as the formation sandstone. If Fickian dispersion is considered appropriately accurate, we suggest the value $\alpha_L = 0.379$ m for longitudinal dispersion coefficient[11], and the relation $\alpha_T = 0.1\alpha_L$ for transverse dispersion coefficient.

4.3 Reporting times
Results should be reported at injection stop, and every 100 years after.

4.4 Additions to reported data
If numerical dispersion gives unphysical plume extents, a threshold of 1% mobile saturation should be applied.
In addition to the original reported data, we suggest to also report the center of mass of mobile CO2, as well as the standard deviation around the center of mass of free phase CO2. Using a 2D birds-eye view of the plume, the standard deviation as obtained from a best-fit Gaussian should have a longitudinal and transverse component.

4.5 Minimum/mandatory complexity

We ask that all participants submit a run with the following complexity, for comparison purposes:

- 2-phase flow with no capillary pressure.
- No dissolution.
- 3D interpretation (actual computation may be in whatever dimension is deemed appropriate).
- Solution up to at least 1000 years after injection.

References


