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A new and extended Sleipner Benchmark model for CO_2 storage simulations in the Utsira Formation

Andrew Cavanagh*, Bamshad Nazarian

Statoil ASA, Trondheim, Norway

Abstract

This paper introduces a new benchmark model for the Sleipner CO_2 storage site. The new Sleipner Benchmark has the same aerial coverage of the original benchmark, but is extended in depth to include the CO_2 layer trapped beneath a thick shale interval. The Sleipner Benchmark is a numerical mesh and geological description of the upper part of the storage site, based on high-resolution 4D seismic mapping of the uppermost layers of CO_2 over the period 1999-2008. This allows for calibrated simulations of a decade of plume dynamics, and prediction of both the free-phase and dissolved CO_2 distributions. Calibrated modeling results from the first Benchmark are presented and discussed with respect to the dynamic equilibrium behavior of the uppermost layer of the plume. The results indicate that the plume is much closer to a stable distribution than previously predicted by modeling, and is likely to further stabilize as a result of significant dissolution in the decades immediately following injection. Benchmark results support a capillary-dominated (layering) and gravity-segregated (flat gas-water contact) interpretation of the Sleipner plume beneath the caprock. The new Benchmark addresses the multi-layered distribution of the entire plume. A conceptual model is presented that clearly distinguishes between Darcy flow and buoyant capillary flow. The stratigraphic alternation of high and low permeability rocks is commonly found in storage formations; however, the baffled nature of stacked CO_2 layering is inherently challenging for reservoir simulation. The new Benchmark will allow modelers to address this challenge by attempting to match the observed CO_2 distribution in the uppermost two layers. This will provide insights into the entire plume dynamics, as well as the nature of CO_2 migration when stored in formations that are characterized by thin shale or siltstone baffles.

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Keywords: CO_2 storage; Sleipner Benchmark; Utsira Formation; numerical model; flow simulation.

* Corresponding author. Tel.: +47 90 27 97 15;
E-mail address: acava@statoil.com

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1. Introduction

The Sleipner Benchmark, originally released by Statoil in 2011, and hosted by IEAGHG[1], has been updated and extended in a new release for 2015. The new Sleipner Benchmark includes an additional model layer (Fig. 1) which allows for high-resolution simulations of the two uppermost layers of CO_2 in the world's largest and longest running offshore CO_2 storage site. These two CO_2 layers lie immediately beneath the caprock, and are separated by a shale layer which acts as a partial barrier (Fig. 1). The Benchmark is particularly valuable in being a real case study with data of sufficient detail and duration to calibrate key uncertainties in CO_2 flow dynamics and storage efficiency[2].

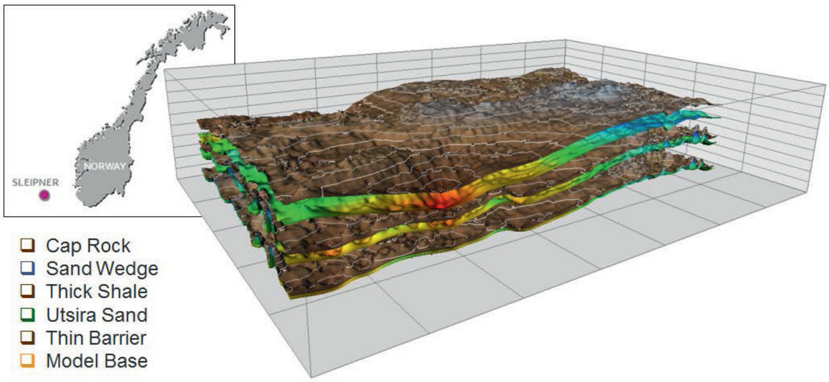

Fig. 1. The new Sleipner Benchmark, viewed from the southeast (3x6 km; 780-880 mbsl); Mesh count: 550,000 cells (50:50:0.5 meters).

This paper presents modeling results based upon the calibrated simulations of the uppermost plume layer for the period 1999-2008. The results provide far-field predictions of the stable CO_2 distribution, and slow dissolution over time, based upon an arrival-rate approximation for CO_2 ingress at the uppermost layer. The calibrated simulation is compared to the observed distribution for 2008. This allows for an accurate approximation of the observed plume distribution to date, and forms the basis of the far-field trapping and solubility simulations. The results, described below, have provided insights which inform the new Sleipner Benchmark. Not least, how to effectively model layered gravity segregation in CO_2 storage sites, given the consequences with respect to plume extent, distribution and storage efficiency, both during and after injection; and reliability of pressure regimes inferred from models.

2. Benchmark results

Sleipner Benchmark modeling results[2,3] have tested the efficacy of vertical equilibrium approaches commonly used in reservoir simulations, and indicated that the best match is derived from a black oil model (Fig, 2), but only when adapted to approximate the near-equilibrium pressure conditions of gravity-segregated flow[4]. The model outcomes are interesting from a flow-dynamics perspective. As the cross-section clearly shows, the simulated gas-water contact is flat, representing a back-filling trap under hydrostatic conditions (Fig. 2).

As such, the topographically-sensitive result is an expression of the near-equilibrium condition for a trapped buoyant fluid, and indicative of gravity-segregated flow. The black oil simulations are initially far from equilibrium, displaying a characteristic coning of CO_2 away from the injection location[2,4]. This is a common feature of all Darcy flow simulations for CO_2 injection into saline formations, and speaks to the underlying dependence on permeability and viscosity-mediated flow in the presence of a non-hydrostatic pressure gradient[4]. However, as the pressure field decays, the redistribution results in an excellent match (Fig. 2). Given the weak pressure field on dissipation, and the governing equation dependence on viscous flow, the simulated compensation is slow. For example, the above simulation match for 2008 occurs approximately 100 years after injection began, and 90 years after injection ceased, circa 2098 (Fig. 2). This long compensation period simply allows the simulation to approach equilibrium.

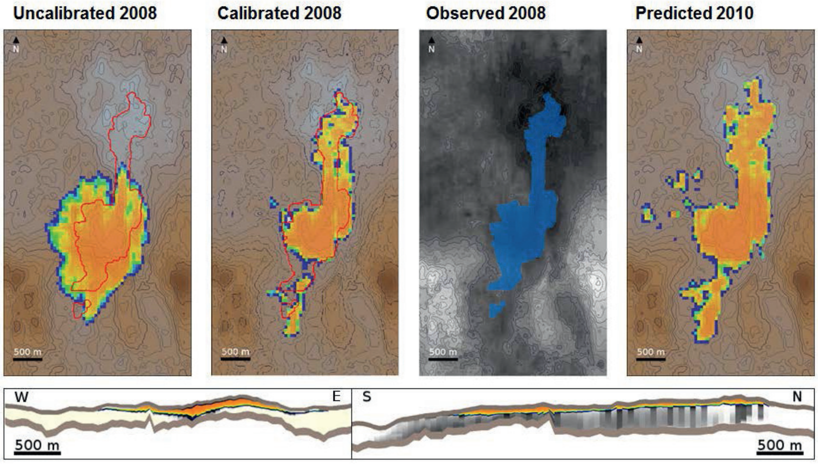

Fig. 2. A near-equilibrium match for 2008 (second panel and right section) to the observed CO_2 distribution below the caprock (third panel, and red outlines). This requires the uncalibrated simulation (left panel and left section) to run forward until 2098, allowing pressure to dissipate after injection. The blue-orange spectrum is low-high gas saturation (orange ~ 80% gas); the greyscale is dissolved CO_2 (black ~ 5 wt%).

The outcome is a significant improvement on the initial black oil simulation output and provides a methodology for calibrating the model to observations: the initial pressure field needs to be compensated for by running the model forward until the overpressure has dissipated and the plume has reached near-equilibrium. For the Sleipner Benchmark simulation, a compensation period of several decades is required. This strongly favors a gravity-segregated/capillary-dominated interpretation of the plume behavior at a relatively short distance from the injection location. The calibrated Benchmark simulation also suggests a significant local dissolution effect within decades (Fig. 3). The black oil simulator handles CO_2 as 'gas' and the formation brine as 'oil', allowing for the miscibility of gas in oil in the reservoir simulation to stand in as a proxy for CO_2 dissolution[5,6]. The simulated dissolution is broadly in agreement with analytical approximations[7], but shows an interesting long-term stagnation and suppression of dissolution in the thin Sand Wedge beneath the caprock, as seen in cross-section (Fig. 2).

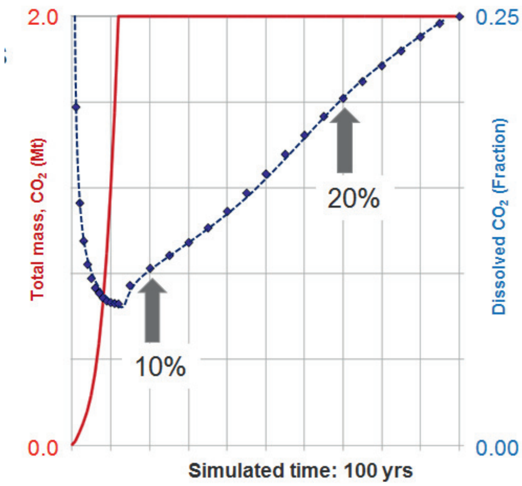

Fig. 3. Dissolved CO_2 as a percentage of the injected mass (2 Mt) for the calibrated simulation. Note the high initial dissolution, which is then suppressed to less than 10% of the injected mass at the end of injection. The dissolution contribution doubles within five decades post-injection.

3. Buoyant capillarity versus viscous flow

Both aspects (buoyant capillary flow and long-term dissolution) are further examined in the new benchmark, with the additional challenge of understanding CO_2 migration between layers (Fig. 4). A range of scenarios are possible for flow communication across the thick shale barrier. A sensitivity analysis of these scenarios for different methodologies (black oil, compositional, invasion percolation) is expected to provide insights into vertical flow across low permeability baffles and barriers within reservoirs. The new Sleipner Benchmark will also help to further develop ideas relating to the apparent need for pressure compensation in Darcy flow models. This has significant implications for all CO_2 storage simulations. Uncalibrated reservoir simulations are likely to over-predict pressure, poorly predict spatial distribution, and underestimate the rapid progression of plume dynamics to equilibrium.

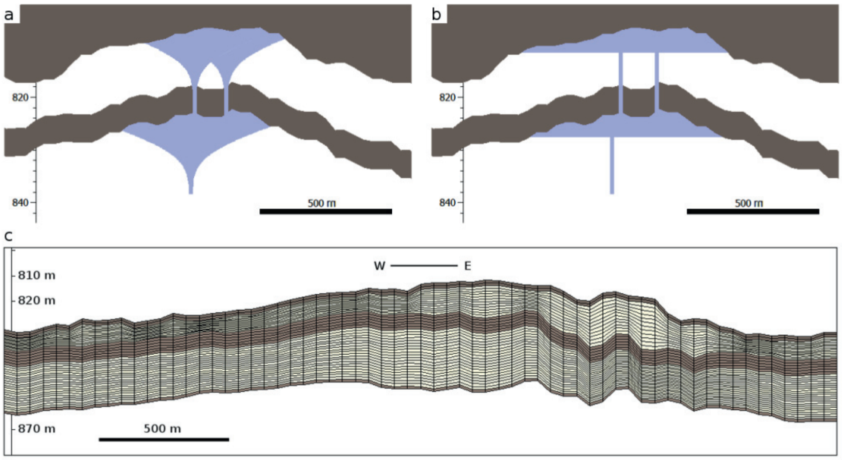

Fig. 4. (a) A conceptual figure of Darcy-mediated viscous flow for the upper two layers; (b) the corresponding conceptual figure for capillary-mediated gravity-dominated flow; (c) the new Sleipner Benchmark in cross-section, with the Sand Wedge separated from the underlying Utsira Formation by a thick shale. A successful match for the observed distribution of CO_2 for the upper layers from 1999-2008 is the new challenge.

4. Conclusion

The current benchmark results clearly indicate that buoyant capillarity is the dominant process in CO_2 storage reservoirs, as befits the non-wetting drainage physics of CO_2 migration. While Darcy's law may characterize the very-near field of the injection well, the predominant flow physics of the storage formation appears to be best described by Young-Laplace[8]. A good approximation of this in a black oil simulation may be arrived at by allowing the pressure in the model to dissipate and the flow to approach its equilibrium position[4]. However, the adaptation of this approach to vertically layered flow across a barrier like the thick shale that separates the uppermost layers in the Sleipner storage site is inherently challenging, and worthy of a new benchmark problem.

In conclusion, benchmark simulations to date indicate that a combination of near-equilibrium conditions in the gravity-segregated layers, and subsequent dissolution of these layers, lowers the dynamic leakage risk associated with the Sleipner storage site. This is currently perceived as extremely low, and is likely to further diminish in the immediate post-operational phase. The new Sleipner Benchmark is expected to further challenge our understanding of the detailed intra-formational plume dynamics and provide further insights into CO_2 storage.

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