Modeling of CO\(_2\) storage in aquifers

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Abstract. Storage of CO\(_2\) in geological formations is a means of mitigating the greenhouse effect. Saline aquifers are a good alternative as storage sites due to their large volume and their common occurrence in nature. The first commercial CO\(_2\) injection project is that of the Sleipner field in the Utsira Sand aquifer (North Sea). Nevertheless, very little was known about the effectiveness of CO\(_2\) sequestration over very long periods of time. In this way, numerical modeling of CO\(_2\) injection and seismic monitoring is an important tool to understand the behavior of CO\(_2\) after injection and to make long term predictions in order to prevent CO\(_2\) leaks from the storage into the atmosphere. The description of CO\(_2\) injection into subsurface formations requires an accurate fluid-flow model. To simulate the simultaneous flow of brine and CO\(_2\) we apply the Black-Oil formulation for two phase flow in porous media, which uses the PVT data as a simplified thermodynamic model. Seismic monitoring is modeled using Biot’s equations of motion describing wave propagation in fluid-saturated poroviscoelastic solids. Numerical examples of CO\(_2\) injection and time-lapse seismics using data of the Utsira formation show the capability of this methodology to monitor the migration and dispersal of CO\(_2\) after injection.

1. Introduction

Fossil-fuel combustion generates carbon dioxide (CO\(_2\)), which is mainly discharged into the atmosphere, increasing its temperature (greenhouse effect). To minimize climate change impacts, geological sequestration of CO\(_2\) is an immediate option [1]. Geologic sequestration involves injecting CO\(_2\) into a target geologic formation at depths typically greater than 1000 m where pressure and temperature are above the critical point for CO\(_2\) (31.6°C, 7.38 MPa).

The CO\(_2\) injection operation at the Sleipner gas field in the North Sea, operated by Statoil and the Sleipner partners, is the world first industrial scale CO\(_2\) injection project designed specifically as a greenhouse gas mitigation measure [1]-[2]. CO\(_2\) separated from natural gas produced at Sleipner is currently being injected into the Utsira Sand, a saline aquifer some 26000 km\(^2\) in area. Injection started in 1996 and is planned to continue for about twenty years, at a rate of about one million tonnes per year.

Time-lapse seismic surveys aim to demonstrate storage integrity, provide early warning should any leakage occur and monitor the migration and dispersal of the CO\(_2\) plume. Recent papers [3]-[4] successfully apply seismic modeling for monitoring the spatio-temporal distribution...
of CO\(_2\) using synthetic generated CO\(_2\) saturation fields. Instead, in this work we employ numerical simulations of CO\(_2\) injection; therefore saturation fields are obtained as a result of the simultaneous flow of CO\(_2\) and brine in porous media.

The final objective is to test that underground storage is a safe and verifiable technology in the long term.

2. The Black-Oil formulation of two-phase flow in porous media

The simultaneous flow of brine and CO\(_2\) is described by the well-known Black-Oil formulation applied to two-phase, two-component fluid flow [5]. In this model, CO\(_2\) may dissolve in the brine but the brine is not allowed to vaporize into the CO\(_2\) phase. This formulation uses, as a simplified thermodynamic model, the following PVT data, determined using the Hassanzadeh’s correlations [6]:

- \(R_s\): CO\(_2\) solubility in brine;
- \(B_{CO_2}\): CO\(_2\) formation volume factor;
- \(B_{b}\): brine formation volume factor.

The nonlinear system of partial differential equation is

\[
\nabla \cdot \left( \frac{k_r \mu}{B_{CO_2}} (\nabla p_{CO_2} - \rho_{CO_2} g \nabla D) \right) + q_{CO_2}
\]

\[
= \frac{\partial}{\partial t} \left[ \phi \left( \frac{S_{CO_2}}{B_{CO_2}} + \frac{R_s S_b}{B_b} \right) \right],
\]

\[
\nabla \cdot \left( \frac{k_r \mu}{B_b} (\nabla p_b - \rho_b g \nabla D) \right) + q_b = \frac{\partial}{\partial t} \left[ \phi \left( \frac{S_b}{B_b} \right) \right].
\]

The unknowns are the fluid pressures \(p_{CO_2}, p_b\) and saturations \(S_{CO_2}, S_b\) for the CO\(_2\) and brine phases. The parameters \(k\) and \(\phi\) are the absolute permeability and porosity respectively. Also, for \(\beta = CO_2, b\), the functions \(k_r\), \(\mu\), and \(\rho\) are the relative permeability, viscosity, and density of the \(\beta\)-phase, respectively.

Two algebraic equations relating the saturations and pressures, complete the system:

\[
S_b + S_{CO_2} = 1, \quad p_{CO_2} - p_b = P_C(S_b),
\]

where \(P_C\) is the capillary pressure.

The solution of the Black-Oil fluid-flow model was obtained employing the public domain software BOAST [7], which solves the differential equations using IMPES, a semi-implicit finite difference technique [8].

3. Biot’s Equations of Motion

Let us consider a 2D isotropic fluid-saturated porous material \(\Omega\). The oscillatory motion of \(\Omega\) at the angular frequency \(\omega\) subject to external sources \(F^{(s)}\) and \(F^{(f)}\) obeys Biot’s equation of motion [3]

\[
-\omega^2 \rho_b \dot{u}^{(s)} - \omega^2 \rho_f \dot{u}^{(f)} - \nabla \cdot \sigma(u) = F^{(s)}
\]

\[
-\omega^2 \rho_f \dot{u}^{(s)} - \omega^2 g u^{(f)} + i \omega b u^{(f)} + \nabla p_f(u) = F^{(f)}.
\]

The unknowns are \(u^{(s)}\) and \(u^{(f)}\), the time Fourier transforms (FT) of the averaged displacement vectors of the solid and fluid phases, respectively. Also, \(\rho_f\) and \(\rho_b\) denote the densities of the single-phase fluid and the bulk material, \(g\) and \(b\) are mass and viscous coupling coefficients, \(\sigma_{ij}\)
is the FT of the stress tensor of the bulk material and $p_f$ is the FT of the fluid pressure. See [4]
for the definition of the variables involved in (4)-(5).

Biot’s equations were solved with the finite element method, employing a 2D non-conforming
finite element space for each component of the solid displacement vector and the vector part of
the Raviart Thomas Nedelec space of zero order for the fluid displacement [9].

4. Numerical Experiments

4.1. Idealized model of the Utsira formation

To test the proposed methodology, we consider an idealized geometrical and physical domain
consisting of 5 regions as shown in Figure 1. The upper 100 m is region $\Omega_1$, a sand of permeability
60 mD and porosity 0.32. $\Omega_2$ is a sealed shale 2 m thick, the top of the Usira formation. Regions
$\Omega_3$ and $\Omega_5$ are the Usira formation, of permeability 1000 mD and porosity 0.37. We assume that
$\Omega_4$ is a sealed shale layer within the Usira sand. The medium was excited with a compressional
point source located at $x= 400$ m, $z= 710$ m.

![Figure 1. Idealized model of the Utsira formation. The injection point is located at $x= 400$ m, $z= 1060$ m.](image)

The Biot model assumes a single-phase fluid, therefore effective fluid density, viscosity
and bulk modulus were obtained using the properties of the CO$_2$ and brine weighted by the
corresponding saturations computed by the fluid-flow simulator.

4.2. Injection Modeling

Figure 2 shows the CO$_2$ saturation distribution after 5 years of injection obtained by the BOAST
simulator. A CO$_2$ accumulation beneath the $\Omega_4$ seal can be clearly observed.

4.3. Seismic Monitoring

Figure 3 displays traces of the vertical component of the particle velocity of the solid phase
before (black curve) and after (red curve) 5 years of CO$_2$ injection. The strong arrival at about
240 ms corresponds to a reflection due to the CO$_2$ accumulation beneath the seal.

Time histories measured near the surface before (left plot) and after 5 years of CO$_2$ injection
(right plot) are shown in Figure 4.

The first reflection in both figures is due to the direct wave coming from the point source
located at $x= 400$ m, $z= 710$ m. The second reflection in the time histories after 5 years, not
observed before the injection, is generated by the CO$_2$ accumulations below the thin shale layer
at depth $z = 940$ m.

Figure 5 displays the vertical component of the solid phase velocity before and after 5 years of
CO$_2$ injection at 200 ms. At this time, the waves generated by the point source have generated
Figure 2. CO$_2$ saturation distribution after 5 years of injection. The injection point is located at $x = 400$ m, $z = 1060$ m.

Figure 3. Traces of particle velocity of the solid phase before and after 5 years of CO$_2$ injection.

Figure 4. Time histories measured near the surface before and after 5 years of CO$_2$ injection.
reflected and transmitted waves due to the CO\(_2\) accumulation below the thin shale layer at z = 940 m.

![Image](image_url)

**Figure 5.** Vertical component of the solid phase velocity at 200 ms before and after 5 years of CO\(_2\) injection.

5. Conclusions

In this work we introduced a methodology to model and monitor CO\(_2\) sequestration using numerical simulations. For that purpose we integrated numerical simulators of CO\(_2\)-brine flow and seismic wave propagation. This methodology was tested with a numerical example showing the capability of seismic monitoring to identify the horizontal and vertical accumulations of CO\(_2\). Therefore, combining fluid-flow simulations with seismic methods constitute an important tool to analyze storage integrity, provide early warning should any leakage occur, and monitor the migration and dispersal of the CO\(_2\) plume.

6. References

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