A numerical procedure to model and monitor CO$_2$ sequestration in aquifers

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Abstract. Carbon Dioxide (CO$_2$) sequestration into geologic formations is a means of mitigating greenhouse effect. In this work we present a new numerical simulation technique to model and monitor CO$_2$ sequestration in aquifers. For that purpose we integrate numerical simulators of CO$_2$-brine flow and seismic wave propagation (time-lapse seismics). The simultaneous flow of brine and CO$_2$ is modeled applying the Black-Oil formulation for two phase flow in porous media, which uses the Pressure-Volume-Temperature (PVT) behavior as a simplified thermodynamic model. Seismic wave propagation uses a simulator based on a space-frequency domain formulation of the viscoelastic wave equation. In this formulation, the complex and frequency dependent coefficients represent the attenuation and dispersion effect suffered by seismic waves travelling in fluid-saturated heterogeneous porous formations. The spatial discretization is achieved employing a nonconforming finite element space to represent the displacement vector. Numerical examples of CO$_2$ injection and time-lapse seismics in the Utsira formation at the Sleipner field are analyzed. The Utsira formation is represented using a new petrophysical model that allows a realistic inclusion of shale seals and fractures. The results of the simulations show the capability of the proposed methodology to monitor the spatial distribution of CO$_2$ after injection.

1. Introduction

Storage of CO$_2$ in geological formations is a procedure employed to reduce the amount of greenhouse gases in the atmosphere to slow down global warming [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 is the world first industrial scale CO$_2$ injection project [1]-[2]. CO$_2$ separated from natural gas produced at Sleipner is 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 monitor the migration and dispersal of the CO$_2$ plume. Recent papers [3]-[4] applied seismic modeling using synthetic generated CO$_2$ saturation...
fields. In this work we combine numerical simulations of CO₂ injection and seismic modeling using a viscoelastic model that takes into account attenuation effects due to the presence of heterogeneities in the solid and fluid properties.

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

The simultaneous flow of brine and CO₂ is described by the well-known Black-Oil formulation applied to two-phase, two component fluid flow [5]. In this model, CO₂ may dissolve in the brine but the brine is not allowed to vaporize into the CO₂ phase. This formulation uses as a simplified thermodynamic model, the PVT data: CO₂ solubility in brine ($R_s$) and CO₂ and brine formation volume factors ($B_{CO₂}$, $B_b$). They are determined using the Hassanzadeh’s correlations [7]. The nonlinear system of partial differential equation is,

$$\nabla \cdot (k \left(\frac{k_{rβ}}{B_{CO₂}μ_{CO₂}} (\nabla p_{CO₂} - ρ_{CO₂} g ∇ D) + \frac{R_s k_{rβ}}{B_b μ_b} (\nabla p_b - ρ_b g ∇ D))\right) + q_{CO₂} = \frac{∂[φ \left(\frac{S_{CO₂}}{B_{CO₂}} + \frac{R_s S_b}{B_b}\right)]}{∂t}, \tag{1}$$

$$\nabla \cdot (k \left(\frac{k_{rβ}}{B_b μ_b} (\nabla p_b - ρ_b g ∇ D)\right) + q_b = \frac{∂[φ(\frac{S_b}{B_b})]}{∂t}. \tag{2}$$

The unknowns are the fluid pressures $p_β$ and saturations $S_β$ for the $β$-phases, with $β = CO₂, b$. The parameters $k$ and $φ$ are the absolute permeability and porosity. Also, the functions $k_{rβ}$, $μ_β$ and $ρ_β$ are the relative permeability, viscosity, and density of the $β$-phase, respectively.

Besides, phase saturations add to one and phase pressures are related by the capillary pressure ($P_C$) relation $p_{CO₂} - p_b = P_C(S_b)$.

The solution of the Black-Oil fluid-flow model was obtained employing the BOAST simulator [8], which solves the flow equations with the IMPES finite difference technique [9].

3. A VISCOELASTIC MODEL FOR WAVE PROPAGATION

The propagation of waves is described using a viscoelastic model that takes into account the dispersion and attenuation effects due to the presence of heterogeneities in the fluid and solid phase properties.

The equation of motion in a 2D isotropic viscoelastic domain $Ω$ with boundary $∂Ω$ can be stated in the space-frequency domain as

$$-\nabla^2 ρ u - ∇ \cdot σ(u) = f(x, φ), \quad Ω \tag{3}$$

$$-σ(u)ν = iωDu, \quad ∂Ω, \tag{4}$$

where $u = (u_x, u_y)$ is the displacement vector. Here ρ is the bulk density and (4) is a first-order absorbing boundary condition using the positive definite matrix $D$.

The stress tensor $σ(u)$ is defined in the space-frequency domain by

$$σ_{jk}(u) = λ_G(φ) ∇ \cdot u δ_{jk} + 2μ_m(φ)ε_{jk}(u), \tag{5}$$

where $σ_{jk}(u)$ and $ε_{jk}(u)$ are the stress and strain tensors, $λ_G$ and $μ_m$ are the complex and frequency dependent Lamé parameters. The Lamé coefficients, computed using White’s model [6] for patchy saturation, take into account attenuation and dispersion of waves due to the presence of CO₂ after injection.

The solution of (3)-(4) was obtained using an iterative finite element domain decomposition procedure employing a nonconforming finite element space, since it generates less numerical dispersion than the standard bilinear elements [3],

2
4. Model of the Utsira Formation and CO₂ Injection.

We consider a 2D model of the Sleipner field constructed using an initial porosity at hydrostatic pressure and the clay content of the formation. The model has 400 m thickness (top at 700 m and bottom 1100 m b.s.l.). Within the formation, there are several mudstone layers which act as barriers to the vertical motion of the CO₂ and can be observed in Figure 1 (left). The viscosity, density and bulk modulus of CO₂ were obtained from the Peng-Robinson equations as a function of temperature and pore pressure [7].

CO₂ is injected at a constant flow rate of one million tons per year. The injection point is located at the bottom of the Utsira formation: \( x = 400 \) m, \( z = 1060 \) m. Figure 1 (right) shows the saturation field after 2 years of CO₂ injection computed using the BOAST flow simulator.

![Porosity map and CO₂ saturation distribution](image)

**Figure 1.** Porosity map (left) and CO₂ saturation distribution (right) after 3 years of injection. The injection point is located at \( x = 600 \) m, \( z = 1060 \) m

5. Time-Lapse Seismic Monitoring

To analyze the capability of seismic monitoring to identify zones of CO₂ accumulation, the media is excited with a compressional point source located at \( x = 400 \) m, \( z = 710 \) m before and after 2 years of CO₂ injection. Time histories measured near the surface are shown in Figures 2 before CO₂ injection (left) and after 2 years of CO₂ injection (right). The upper reflection in both figures is due to the direct wave coming from the point source. The other reflection in (b) is due to the CO₂ accumulations below the deepest mudstone layer. Figure 3 displays the traces measured at \( x = 750 \) m, \( z = 710 \) m shown in Figure 2.

6. Conclusions

In this work we presented a new numerical methodology to model and monitor CO₂ sequestration. For that purpose we integrated numerical simulators of CO₂-brine flow and seismic wave propagation. The numerical experiment shows the capability of seismic monitoring to identify the spatial distribution of CO₂ after injection. Therefore, this approach constitute a valuable tool to analyze storage integrity, provide early warning should any leakage occur, and monitor the migration and dispersal of the CO₂ plume.

7. References

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Figure 2. Traces of the z-component of the displacement before (left) and after (right) 2 years of CO\textsubscript{2} injection. The second reflection is due to the deepest CO\textsubscript{2} accumulation.

Figure 3. Traces of particle velocity of the solid phase before and after 2 years of CO\textsubscript{2} injection.

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