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The ground as energy source and storage

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Efficiency of shaft sealing for CO$_2$ sequestration in coal mines

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EAGE
Introduction

Economic growth
Energy demand
Fossil fuels consumption
Carbon dioxide emissions
Greenhouse effect
Global warming

Different approaches to mitigate climate change:
- Improve energy efficiency;
- Increase use of renewable energy or nuclear power;
- Reforestation;
- CO$_2$ capture and storage.
- Geological sequestration, e.g. deep unmineable coal seams.
Different approaches to mitigate climate change:

- Improve energy efficiency;
- Increase use of renewable energy or nuclear power;
- Reforestation;
- \( CO_2 \) capture and storage.
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Geological sequestration, e.g. deep unmineable coal seams.
Anderlues coal mine

Figure: Map of the outcropping or shallow subsurface coal basins (shaded area) in and around Belgium. Modified after [Piessens and Dusar, 2006].

Host rocks

= Westphalian formations (313-304 Ma)

= 60% shale + 37% sandstone + 3% coal

1857-1969: Coal exploitation, **only 3.5%** of the total coal volume **extracted**

1978-2000: Former coal mine used as a reservoir for **storage of natural gas**
Shaft sealing system

Gas sequestrated in the deep geological formation through the shafts.

Sealing system required Efficiency?

Figure: Layout of the sealing system used for the shaft n°6 of Anderlues coal mine.
Shaft sealing system

Gas sequestrated in the deep geological formation **through the shafts.**

Sealing system required

Efficiency?

Numerical modelling with the FE code Lagamine

**Figure:** Layout of the sealing system used for the shaft n°6 of Anderlues coal mine.
Two-dimensional axisymmetric analysis:

Materials considered in the first model: host rock, concrete, bentonite and backfill.

Figure: Geometry and boundary conditions used for the hydromechanical analysis.
Modelling

Two-dimensional axisymmetric analysis:

**Materials considered** in the first model: host *rock, concrete, bentonite* and *backfill*.

4 different stages:

1. **Shaft excavation** (50 days)
2. **Set-up of the concrete** shaft lining and ventilation of the mine (50 years)
3. **Set-up of the sealing system** (50 days)
4. **Injection** of $\text{CO}_2$ into the mine (500 years)

**Figure**: Geometry and boundary conditions used for the hydromechanical analysis.
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4. Injection of CO₂ into the mine (500 years)

Figure: Geometry and boundary conditions used for the hydromechanical analysis.
First 3 steps = establishment of the hydro-mechanical conditions before CO$_2$ injection.

1. **Shaft excavation** (50 days)
2. **Set-up** of the **concrete** shaft lining and ventilation of the mine (50 years)
3. **Set-up** of the **sealing system** (50 days)
4. **Injection** of CO$_2$ into the mine (500 years)

**Figure:** Evolution of pore water pressure profiles in the shale during the shaft excavation.
3 balance equations:

- **stress equilibrium** equation
- mass balance equation for **water**
- mass balance equation for **CO₂**

2 phases flow model

2 transport processes

- **advection** of each phase (Darcy’s law)
- **diffusion** of the components within each phase (Fick’s law)
Modelling

- **3 balance equations:**
  - stress equilibrium equation
  - mass balance equation for water
  - mass balance equation for CO$_2$

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**2 phases flow model**

**2 transport processes**
- **advection** of each phase (Darcy’s law)
- **diffusion** of the components within each phase (Fick’s law)
Figure: Evolution of gas pressures in the different materials during $CO_2$ storage in the coal mine.

Increase in gas pressure essentially localized in the concrete elements.
Table: Contribution of the different materials to the total mass of CO$_2$ rejected to the atmosphere, determined at 50m depth.

<table>
<thead>
<tr>
<th>Time</th>
<th>Backfill</th>
<th>Concrete</th>
<th>Shale</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 year</td>
<td>9 kg</td>
<td>0.02 kg</td>
<td>0.20 kg</td>
</tr>
<tr>
<td>5 years</td>
<td>4761 kg</td>
<td>0.52 kg</td>
<td>0.96 kg</td>
</tr>
<tr>
<td>10 years</td>
<td>3.49E04 kg</td>
<td>3.34 kg</td>
<td>1.42 kg</td>
</tr>
<tr>
<td>50 years</td>
<td>4.15E05 kg</td>
<td>31.67 kg</td>
<td>2.63 kg</td>
</tr>
<tr>
<td>100 years</td>
<td>8.52E05 kg</td>
<td>53.42 kg</td>
<td>3.72 kg</td>
</tr>
<tr>
<td>250 years</td>
<td>2.09E06 kg</td>
<td>93.13 kg</td>
<td>6.96 kg</td>
</tr>
<tr>
<td>500 years</td>
<td>4.11E06 kg</td>
<td>140.80 kg</td>
<td>11.96 kg</td>
</tr>
</tbody>
</table>

Reference case:

\[ S_{r,w} = 90\% ; \quad K_{int,\text{shale}} = 2 \cdot 10^{-19} m^2 ; \quad K_{int,\text{concrete}} = 1 \cdot 10^{-16} m^2. \]

Because of its high permeability, the **backfill drains almost all CO$_2$ fluxes.**
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Because of its high permeability, the backfill drains almost all $CO_2$ fluxes.

Figure: Parameters analysis, mass rejected after 500 years.
Mass balance equation for $CO_2$

\[
div(f_{CO_2}) + \frac{\partial}{\partial t} (\rho_{CO_2} \phi (1 - S_{r,w})) + div(f_{CO_2 - d}) + \frac{\partial}{\partial t} (\rho_{CO_2 - d} \phi S_{r,w}) = Q_{CO_2}
\]

where $f$ is the total mass flow, $\rho$ is the bulk density, $\phi$ is the porosity, $S_{r,w}$ is the water degree of saturation, $Q$ is the volume source.

Dry $CO_2$ in gas phase

Dissolved $CO_2$ in water

\[
\]

F. Bertrand, R. Charlier, F. Collin & A.-C. Dieudonné (University of Liège)
Modelling considering coal

Mass balance equation for $CO_2$ taking into account adsorption:

\[
\begin{align*}
\text{Dry } CO_2 \text{ in gas phase} & : \quad \text{div}(f_{CO_2}) + \frac{\partial}{\partial t}(\rho_{CO_2} \phi(1 - S_{r,w})) \\
\text{Dissolved } CO_2 \text{ in water} & : \quad \text{div}(f_{CO_2-d}) + \frac{\partial}{\partial t}(\rho_{CO_2-d} \phi S_{r,w}) \\
\text{Adsorbed } CO_2 \text{ on coal} & : \quad \frac{\partial}{\partial t}((1 - \phi)\rho_{std_{CO_2}} \rho_{coal} V_{ad}) = Q_{CO_2}
\end{align*}
\]

where \( f \) is the total mass flow, \( \rho \) is the bulk density, \( \phi \) is the porosity, \( S_{r,w} \) is the water degree of saturation, \( Q \) is the volume source and \( V_{ad} \) is the adsorbed volume of $CO_2$ per unit of mass of coal.
Modelling considering coal

Mass balance equation for CO₂ taking into account adsorption:

\[
\text{div}(f_{CO₂}) + \frac{\partial}{\partial t} (\rho_{CO₂} \phi (1 - S_{r,w})) + \text{div}(f_{CO₂ - d}) + \frac{\partial}{\partial t} (\rho_{CO₂ - d} \phi S_{r,w}) + \frac{\partial}{\partial t} (\rho_{\text{stdCO₂}} \rho_{\text{coal}} V_{ad}) = Q_{CO₂}
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where \( f \) is the total mass flow, \( \rho \) is the bulk density, \( \phi \) is the porosity, \( S_{r,w} \) is the water degree of saturation, \( Q \) is the volume source and \( V_{ad} \) is the adsorbed volume of CO₂ per unit of mass of coal.

\( V_{ad} \) determined by a Langmuir Isotherm:

\[
V_{ad} = \frac{V_L \cdot P}{P_L + P}
\]

where \( P \) is the gas pressure and \( V_L \) and \( P_L \) are two parameters.

[Wu et al., 2011] : \( V_L = 0.0477 \text{m}^3/\text{kg} \) ; \( P_L = 1.38 \text{MPa} \)
Modelling
considering coal - 1D

Coalbed
Gas Injection
25m
2,5m

Without coal

\[ 1 \times 10^5 \text{ s} \quad 1 \times 10^6 \text{ s} \quad 1 \times 10^7 \text{ s} \quad 1 \times 10^8 \text{ s} \quad 1 \times 10^9 \text{ s} \quad 1 \times 10^{10} \text{ s} \]

With one coal seam 2.5 meters wide

CO \[ \text{_2} \] rejected (300 years): 6% without coal \[ \rightarrow 0.03\% \text{ with the coal.} \]
Modelling considering coal - 1D

Without coal

25m

With one coal seam 2.5 meters wide

CO$_2$ rejected (300 years):
6% without coal → 0.03% with the coal.

F. Bertrand, R. Charlier, F. Collin & A.-C. Dieudonné (University of Liège)
Modelling considering coal - 1D

Without coal

With one coal seam 2.5 meters wide

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Modelling considering coal - 1D

CO₂ rejected (300 years): 6% without coal → 0.03% with the coal.
Back to the shaft sealing **considering a coal seam 0, 25\,m wide above the injection zone.**

![Graph showing rejected mass of CO₂ over time for different materials and conditions.](image)

-20% rejected after 250 years
Modelling considering coal - 2D

Back to the shaft sealing **considering a coal seam 0, 25 m wide above the injection zone.**

-20% rejected after 250 years
Modelling considering coal + shale anisotropy
Modelling considering coal + shale anisotropy

Mechanical anisotropy

Hydraulic anisotropy

$k_\perp$ ; $k_\parallel$
Modelling considering coal + shale anisotropy

Mechanical anisotropy

Hydraulic anisotropy $k_\perp ; k_{\parallel}$

Rejected mass of $CO_2$ (after 500 years)

Anisotropic cases: $10 \cdot k_\perp = k_{\parallel}$
Better understanding of the CO\textsubscript{2} transfer mechanisms through and around a shaft and its sealing system (Anderlues).

Realistic values for the parameters + sensitivity analysis + HM conditions reproduced

- Concrete permeability > Host rock permeability
  \[\text{CO}_2\] preferentially flows through the concrete then the backfill.

- Bentonite buffer has shown limited efficiency as \text{CO}_2 by-passes it to flow through the concrete support. Design?

- Due to adsorption, coal has a favourable impact on gas leakage.

- Depending on bedding plan orientation, shale anisotropy can also have a favourable impact on gas leakage.
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- Due to **adsorption**, coal has a **favourable impact** on gas leakage.

- Depending on bedding plan orientation, **shale anisotropy** can also have a favourable impact on gas leakage.
Conclusions

Future works

$CO_2$ injection = **stimulation** for coalbed **methane recovery**

$\Delta S_{r,w} \Rightarrow \text{Shrinkage/Swelling} \Rightarrow \Delta k$

Take into account **couplings at the micro-scale**

via a multi-scale finite element method.
Thank you for your attention!

**Stress equilibrium** equation

\[ \text{div}(\sigma) + b = 0 \]

**Mass balance equation for water**

\[ \text{div}(f_w) + \frac{\partial}{\partial t} (\rho_w \phi S_{r,w}) + \text{div}(f_v) + \frac{\partial}{\partial t} (\rho_v \phi (1 - S_{r,w})) = Q_w \]

- Liquid water
- Water vapour

**Mass balance equation for CO}_2\)**

\[ \text{div}(f_{CO}_2) + \frac{\partial}{\partial t} (\rho_{CO}_2 \phi (1 - S_{r,w})) + \text{div}(f_{CO}_2-d) + \frac{\partial}{\partial t} (\rho_{CO}_2-d \phi S_{r,w}) + \frac{\partial}{\partial t} ((1 - \phi)\rho_{stdCO}_2 \rho_{coal} \gamma_{ad}) = Q_{CO}_2 \]

- Dry \(CO}_2\) in gas phase
- Dissolved \(CO}_2\) in water
- Adsorbed \(CO}_2\) on coal
Additional Information
Coupled HM formulation

- Mass flows: advection + diffusion
  
  \[ f_w = \rho_w q_l \]
  \[ f_v = \rho_v q_g + i_v \]
  \[ f_{CO_2} = \rho_{CO_2} q_g + i_{CO_2} \]
  \[ f_{CO_2-d} = \rho_{CO_2-d} q_g + i_{CO_2-d} \]

- Advection: Darcy’s law
  
  \[ q_l = -\frac{K_{int} \cdot k_{rw}}{\mu_w} \left( \text{grad}(\rho_w) + g \rho_w \text{grad}(y) \right) \]
  \[ q_g = -\frac{K_{int} \cdot k_{rg}}{\mu_g} \left( \text{grad}(\rho_g) + g \rho_g \text{grad}(y) \right) \]

- Diffusion: Fick’s law
  
  \[ i_v = -\phi (1 - S_{r,w}) \tau D_{v/CO_2} \rho_g \text{grad} \left( \frac{\rho_v}{\rho_g} \right) = -i_{CO_2} \]
  \[ i_{CO_2-d} = -\phi S_{r,w} \tau D_{CO_2-d/w} \rho_w \text{grad} \left( \frac{\rho_{CO_2-d}}{\rho_w} \right) \]
### Mechanical properties

<table>
<thead>
<tr>
<th></th>
<th>Coal</th>
<th>Shale</th>
<th>Concrete</th>
<th>Bentonite</th>
<th>Backfill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus (MPa)</td>
<td>$E$</td>
<td>2710</td>
<td>3000</td>
<td>33</td>
<td>150</td>
</tr>
<tr>
<td>Poisson’s ration</td>
<td>$\nu$</td>
<td>0.34</td>
<td>0.3</td>
<td>0.16</td>
<td>0.3</td>
</tr>
<tr>
<td>Cohesion (MPa)</td>
<td>$c$</td>
<td>-</td>
<td>2.66</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Friction angle (°)</td>
<td>$\phi$</td>
<td>-</td>
<td>22.7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Biot coefficient</td>
<td>$b$</td>
<td>1</td>
<td>0.4</td>
<td>0.8</td>
<td>1</td>
</tr>
</tbody>
</table>

**Table:** Mechanical properties
Additional Information

Hydraulic properties

Van Genuchten model to relate suction with degree of saturation:

\[ S_{r,w} = \left[ 1 + \left( \frac{s}{P_r} \right)^n \right]^{-m} \]

Van Genuchten water relative permeability model:

\[ k_{rw} = \sqrt{S_{r,w}} \left( 1 - \left( 1 - S_{r,w}^{-m} \right)^m \right)^2 \]

Gas relative permeability model:

\[ k_{rg} = (1 - S_{r,w})^3 \]

<table>
<thead>
<tr>
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</tr>
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<tbody>
<tr>
<td><strong>Intrinsic permeability (m²)</strong></td>
<td>( K_{int} )</td>
<td>2E-19</td>
<td>1E-16</td>
<td>8E-21</td>
</tr>
<tr>
<td><strong>Porosity</strong></td>
<td>( \phi )</td>
<td>0.054</td>
<td>0.15</td>
<td>0.37</td>
</tr>
<tr>
<td><strong>Tortuosity</strong></td>
<td>( \tau )</td>
<td>0.25</td>
<td>0.25</td>
<td>0.0494</td>
</tr>
<tr>
<td><strong>Van Genuchten parameter (MPa)</strong></td>
<td>( P_r )</td>
<td>9.2</td>
<td>2</td>
<td>16</td>
</tr>
<tr>
<td><strong>Van Genuchten parameter</strong></td>
<td>( n )</td>
<td>1.49</td>
<td>1.54</td>
<td>1.61</td>
</tr>
<tr>
<td><strong>Van Genuchten parameter</strong></td>
<td>( m )</td>
<td>0.33</td>
<td>0.35</td>
<td>0.38</td>
</tr>
</tbody>
</table>

**Table:** Hydraulic parameters
For coal:

\[ S_{r,w} = \frac{1}{100} \left( CSR1 \cdot \log \left( \frac{s}{10^6} \right) + CSR2 \right) \]

\[ k_{rw} = \frac{(S_{r,w} - S_{res})^{CKW1}}{(1 - S_{res})^{CKW2}} \]

\[ k_{rg} = CKA3 \cdot (1 - S_e)^{CKA1} \cdot (1 - S_e^{CKA2}) \quad \text{with} \quad S_e = \frac{S_{r,w} - S_{res}}{1 - S_{res}} \]

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<tr>
<td>CSR1</td>
<td>-7.5</td>
</tr>
<tr>
<td>CSR1</td>
<td>1</td>
</tr>
<tr>
<td>CKW1</td>
<td>30.2</td>
</tr>
<tr>
<td>CKW2</td>
<td>30.2</td>
</tr>
<tr>
<td>CKA1</td>
<td>0.5</td>
</tr>
<tr>
<td>CKA2</td>
<td>10.2</td>
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<tr>
<td>CKA3</td>
<td>0.65</td>
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### Table: Hydraulic parameters for coal

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<th>Parameter</th>
<th>Value</th>
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<td>Intrinsic permeability (m²)</td>
<td>1E-16</td>
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Mechanical shale anisotropy:

- Elasticity (Orthotropy): $E_\parallel$, $E_\perp$, $\nu_\parallel$, $\nu_\perp$, $G_\parallel$, $G_\perp$
- Plasticity: anisotropy through the cohesion

Hydraulic anisotropy:

$$k_\perp; k_\parallel$$
Coalbeds = dual porosity systems

Micropores + Macropores $\iff$ Matrix + Cleats

Figure: [Schlumberger, 2015]
Coalbeds = dual permeability systems

Matrix permeability $<<$ Permeability of the cleat system

Fick’s law of diffusion in the coal matrix $>>$ Darcy’s law in the fracture system

Cleat permeability is directly dependent on the width of the cleats.

Figure: [Schlumberger, 2015]
Additional Information

Future works: $FE^2$

Apply a **multi-scale method** taking advantage of the **periodical structure of coal**.
Constitutive equations (flow law, storage law) are applied only on the microscopic scale.

Homogenization equations are employed to compute the macroscopic flows knowing the pore pressure state at microscopic scale.