Reservoir scale CO$_2$ plume migration prediction with deep neural networks

Gege Wen
Challenge:
Numerical simulation for CO$_2$-water multiphase flow is very computationally expensive.
Challenge:
Numerical simulation for CO$_2$-water multiphase flow is very computationally expensive.

Goal:
A deep learning algorithm that can generate accurate predictions of the multiphase flow process with high efficiency.
Challenge:
Numerical simulation for CO$_2$-water multiphase flow is very computationally expensive.

Goal:
A deep learning algorithm that can generate accurate predictions of the multiphase flow process with high efficiency.

Method:
Use numerical simulator to generate training data of plume migration results. Use the data to train deep neural network models.
Scientific Approach

What we (might) have:

**Reservoir condition**
- Initial pressure
- Temperature
- Salinity

**Geological model**
- Permeability
- Porosity
- Anisotropy ratio

**Rock properties**
- Relative permeability
- Capillary pressure
- Compressibility

**Injection design**
- Injection rate
- Injection duration
- Perforation interval
Scientific Approach

What we (might) have:

<table>
<thead>
<tr>
<th>Reservoir condition</th>
<th>Geological model</th>
<th>Rock properties</th>
<th>Injection design</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Initial pressure</td>
<td>- Permeability</td>
<td>- Relative permeability</td>
<td>- Injection rate</td>
</tr>
<tr>
<td>- Temperature</td>
<td>- Porosity</td>
<td>- Capillary pressure</td>
<td>- Injection duration</td>
</tr>
<tr>
<td>- Salinity</td>
<td>- Anisotropy ratio</td>
<td>- Compressibility</td>
<td>- Perforation interval</td>
</tr>
</tbody>
</table>

What we use:

Numerical simulator
Scientific Approach

What we (might) have:

- **Reservoir condition**
  - Initial pressure
  - Temperature
  - Salinity

- **Geological model**
  - Permeability
  - Porosity
  - Anisotropy ratio

- **Rock properties**
  - Relative permeability
  - Capillary pressure
  - Compressibility

- **Injection design**
  - Injection rate
  - Injection duration
  - Perforation interval

What we use:

- Numerical simulator

What we want:

- CO₂ plume distribution
- Pressure distribution
- Trapping mechanism
Scientific Approach

What we (might) have:

- **Reservoir condition**
  - Initial pressure
  - Temperature
  - Salinity

- **Geological model**
  - Permeability
  - Porosity
  - Anisotropy ratio

- **Rock properties**
  - Relative permeability
  - Capillary pressure
  - Compressibility

- **Injection design**
  - Injection rate
  - Injection duration
  - Perforation interval

What we use:

- **Numerical simulator**

What we want:

- **CO₂ plume distribution**
- Pressure distribution
- Trapping mechanism

---

Probabilistic assessment

History matching
Scientific Approach

What we (might) have:

- **Reservoir condition**
  - Initial pressure
  - Temperature
  - Salinity

- **Geological model**
  - Permeability
  - Porosity
  - Anisotropy ratio

- **Rock properties**
  - Relative permeability
  - Capillary pressure
  - Compressibility

- **Injection design**
  - Injection rate
  - Injection duration
  - Perforation interval

What we use:

- **ML model**

What we want:

- **CO₂ plume distribution**
- **Pressure distribution**
- **Trapping mechanism**
Scientific Approach – 2D radial system

Reservoir condition
- Initial pressure
- Temperature
- Salinity

Geological model
- Permeability
  - Porosity
  - Anisotropy ratio

Rock properties
- Relative permeability
- Capillary pressure
- Compressibility

Injection design
- Injection rate
- Injection duration
- Perforation interval

CO₂ plume distribution
Pressure distribution
Trapping mechanism
Scientific Approach – 2D radial system

Reservoir condition
- Initial pressure
- Temperature
- Salinity

Geological model
- Permeability
- Porosity
- Anisotropy ratio

Rock properties
- Relative permeability
- Capillary pressure
- Compressibility

Injection design
- Injection rate
- Injection duration
- Perforation interval

CO₂ plume distribution

Pressure distribution

Trapping mechanism
Scientific Approach – 2D radial system

**Reservoir condition**
- Initial pressure
- Temperature
- Salinity

**Geological model**
- Permeability
  - Porosity
  - Anisotropy ratio

**Rock properties**
- Relative permeability
- Capillary pressure
- Compressibility

**Injection design**
- Injection rate
- Injection duration
- Perforation interval

**EOS Gas model**
- Input
  - $y_{CO2}$ Pressure
- Output
  - Gas density

**EOS Liquid model**
- Input
  - $x_{CO2}$ Pressure
  - Temperature
- Output
  - Liquid density

**Pressure distribution**
- Output
  - Pressure

**CO$_2$ plume distribution**
Scientific Approach – 2D radial system

**Reservoir condition**
- Initial pressure
- Temperature
- Salinity

**Geological model**
- Permeability
  - Porosity
  - Anisotropy ratio

**Rock properties**
- Rel permeability
- Capillary pressure
- Compressibility

**Injection design**
- Injection rate
- Injection duration
- Perforation interval

**CO₂ plume distribution**

**Pressure distribution**

**Trapping mechanism**

---

Stanford Center for Carbon Storage
General machine learning task procedure

Step 1  Data Preparation
Step 2  Model Training
Step 3  Model Prediction
2D reservoir ML model task procedure

<table>
<thead>
<tr>
<th>Training Input</th>
<th>Test Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permeability</td>
<td>Permeability</td>
</tr>
<tr>
<td>Init pressure</td>
<td>Init pressure</td>
</tr>
<tr>
<td>Temperature</td>
<td>Temperature</td>
</tr>
<tr>
<td>Inj rate</td>
<td>Inj rate</td>
</tr>
<tr>
<td>Pc cap scaling factor</td>
<td>Pc cap scaling factor</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Training Output</th>
<th>Test Output</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="SG, t = 12 year" /></td>
<td><img src="image" alt="SG, t = 12 year" /></td>
</tr>
</tbody>
</table>

**Step 1**
Data Preparation

**Step 2**
Model Training

**Step 3**
Model Prediction
2D reservoir ML model task procedure

### Training Input
- Permeability
- Init pressure
- Temperature
- Inj rate

### Training Output
- Neq (Rel perm (Swi))

### Test Input
- Permeability
- Init pressure
- Temperature
- Inj rate

### Test Output
- Neq (Rel perm (Swi))

---

**Step 1**
Data Preparation

**Step 2**
Model Training

**Step 3**
Model Prediction
Training Input

Injection rate
Perforation interval
Initial pressure
Reservoir temperature

Irreducible water saturation
van Genuchten scaling factor
CO₂ gas saturation field - data of neural network

24 time steps with a total of 30 years
2D reservoir ML model task procedure

<table>
<thead>
<tr>
<th>Training Input</th>
<th>Training Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permeability</td>
<td>SG, t = 12 year</td>
</tr>
<tr>
<td>Init pressure</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td></td>
</tr>
<tr>
<td>Inj rate</td>
<td></td>
</tr>
<tr>
<td>Pcap scaling factor</td>
<td></td>
</tr>
</tbody>
</table>

**Step 1**
Data Preparation

**Step 2**
Model Training

**Step 3**
Model Prediction

<table>
<thead>
<tr>
<th>Test Input</th>
<th>Test Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permeability</td>
<td>SG, t = 12 year</td>
</tr>
<tr>
<td>Init pressure</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td></td>
</tr>
<tr>
<td>Inj rate</td>
<td></td>
</tr>
<tr>
<td>Pcap scaling factor</td>
<td></td>
</tr>
</tbody>
</table>

- **Numerical Simulator**
- **Neural Network**
Temporal 3D-Net Model Architecture

- Encoder: extract hidden dimension information from the input
- Connecting: map hidden dimension input to output
- Decoder: map hidden dimension output to physical space

~7 million parameters
Trained on Graphics Processing Unit (GPU) for days to weeks

3D ResNet
2D reservoir ML model task procedure

<table>
<thead>
<tr>
<th>Step 1</th>
<th>Step 2</th>
<th>Step 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Preparation</td>
<td>Model Training</td>
<td>Model Prediction</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Training Input</th>
<th>Test Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permeability, Inj perforation</td>
<td>Permeability, Inj perforation</td>
</tr>
<tr>
<td>Init pressure, Inj duration</td>
<td>Init pressure, Inj duration</td>
</tr>
<tr>
<td>Temperature, Rel perm (Swi)</td>
<td>Temperature, Rel perm (Swi)</td>
</tr>
<tr>
<td>Inj rate, Pcap scaling factor</td>
<td>Inj rate, Pcap scaling factor</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Training Output</th>
<th>Test Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>SG, t = 12 year</td>
<td>SG, t = 12 year</td>
</tr>
</tbody>
</table>
Test set example – CO$_2$ saturation

ML~0.5 s
ECLIPSE~30 m
CO₂ saturation distribution prediction

Mean absolute error: 0.0012
Absolute error std: 0.0055

Mean plume abs error: 0.0086
Absolute plume abs error std: 0.013

Mean absolute error: 0.0013
Absolute error std: 0.0060

Mean plume abs error: 0.0091
Absolute plume abs error std: 0.014
Pressure buildup distribution prediction

Mean relative error: 0.023
Relative error std: 0.051

Mean relative error error: 0.025
Relative error std: 0.058
Test set example – Molar fraction of dissolved CO$_2$
Test set example – Molar fraction of dissolved CO$_2$
Trained ML model is served as a web application
Summary

Reservoir condition
• Initial pressure
• Temperature
  • Salinity

Geological model
• Permeability
  • Porosity
  • Anisotropy ratio

Rock properties
• Relative permeability
• Capillary pressure
  • Compressibility

Injection design
• Injection rate
• Injection duration
• Perforation interval

CO₂ plume distribution

Pressure distribution

Trapping mechanism
Thank you for listening!

We acknowledge ExxonMobil for supporting this work.